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Near detectors for long-baseline physics – the T2K experience

Mark Scott
20th June 2023

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Near detectors for long-baseline physics – the ~~T2K~~ Mark S experience

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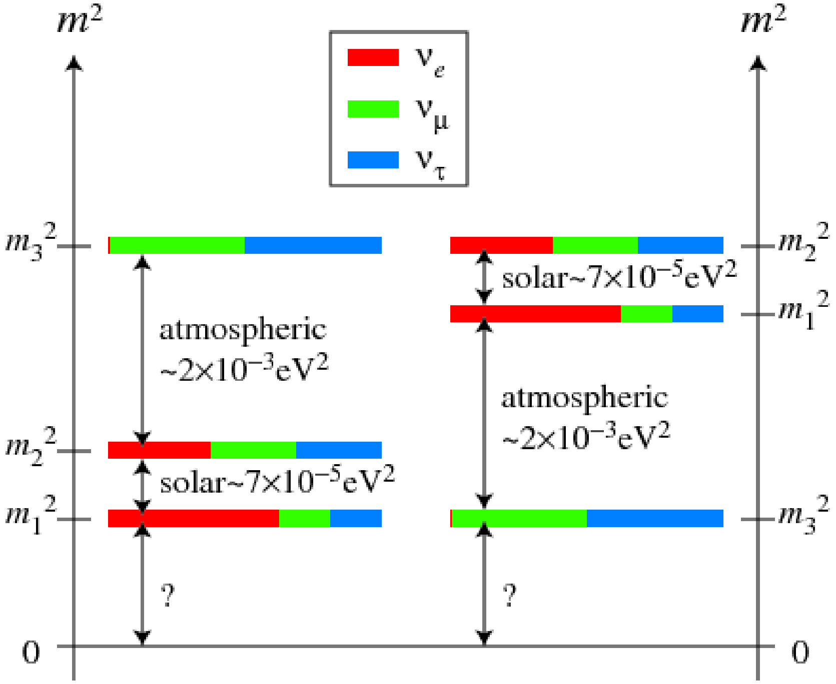
Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



What **do** we know (PDG ‘22)?

- $\theta_{23} = 47.2^o \pm 1.3^o$
- $\theta_{13} = 8.5^o \pm 0.1^o$
- $\theta_{12} = 33.6^o \pm 0.8^o$
- $|\Delta m^2_{32}| = (2.536 \pm 0.03) \times 10^{-3}$ eV^{2}c^{-4}
- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^{2}c^{-4}

What **don’t** we know?

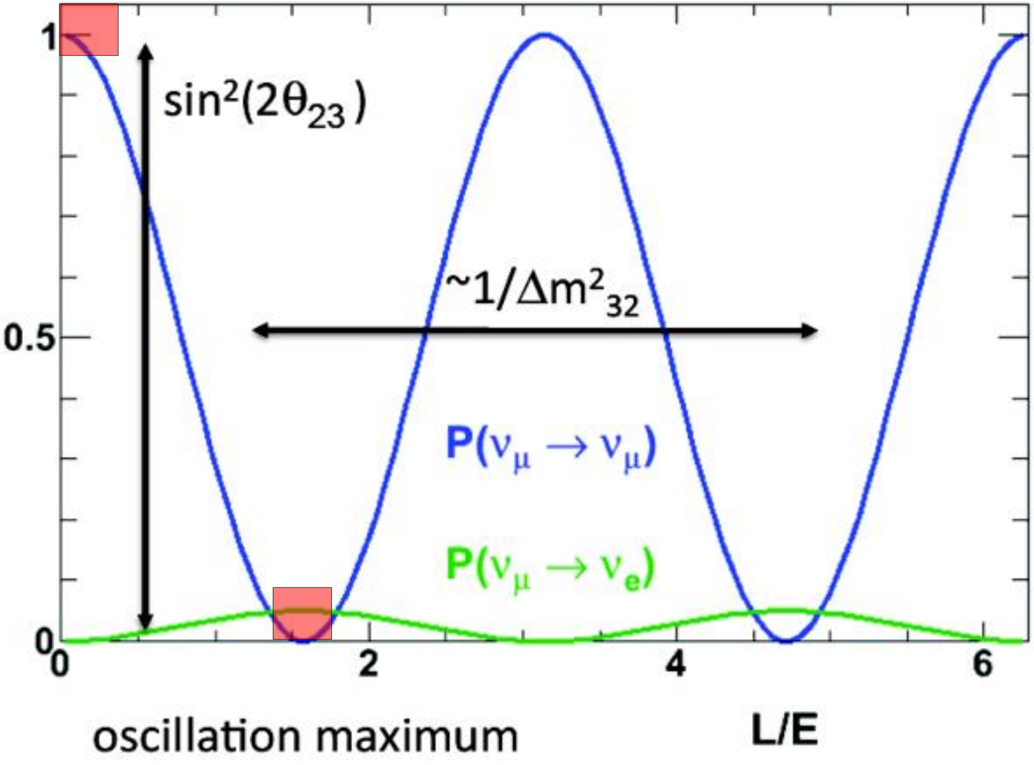
- Is θ_{23} == 45^o (octant)?
- Is $\Delta m^2_{32} > 0$ (mass ordering)?
- Do neutrinos violate CP-symmetry?
- New physics?

Long-baseline neutrino experiments

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- Need to sample spectrum at different values of L/E
- Build two detectors
- One close to neutrino source
- Other at maximal oscillation

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Electron (anti)neutrino appearance

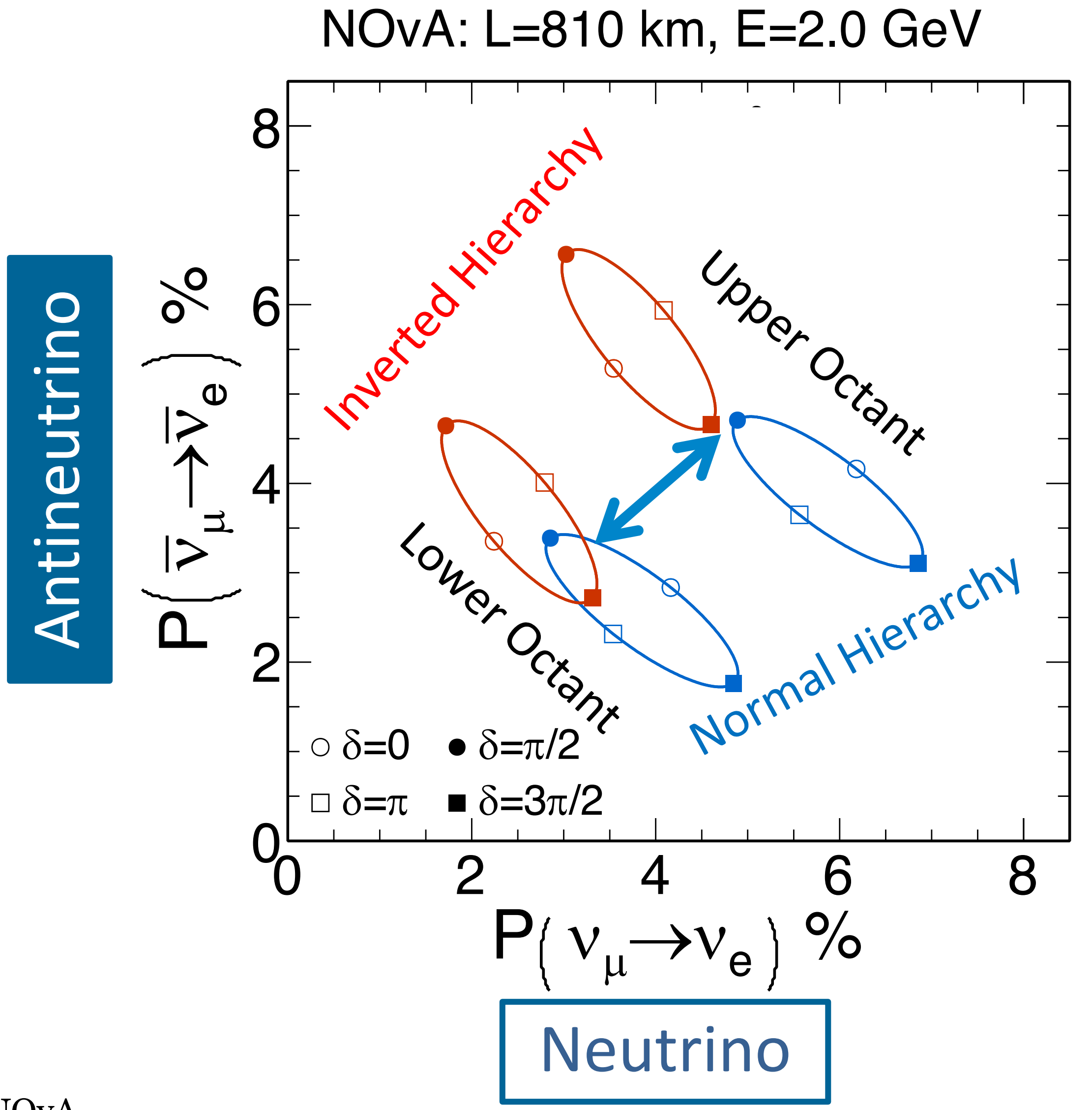
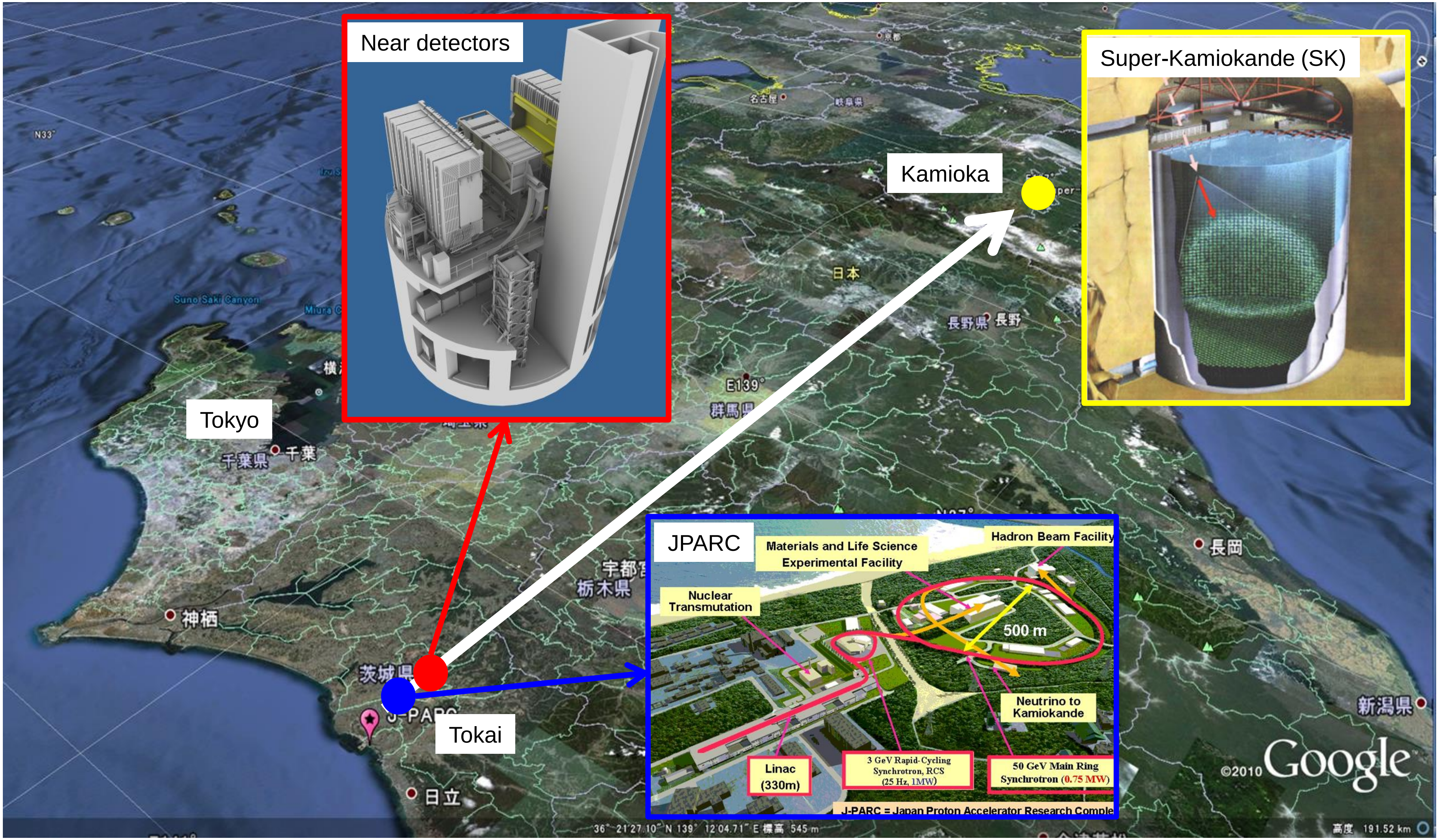
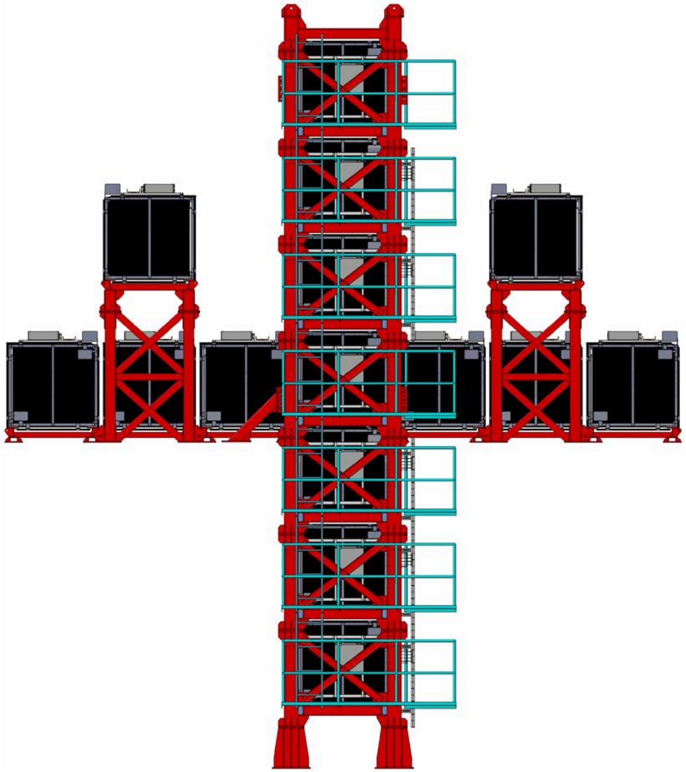


Image by A. Himmel / NOvA

Tokai to Kamioka Experiment – T2K

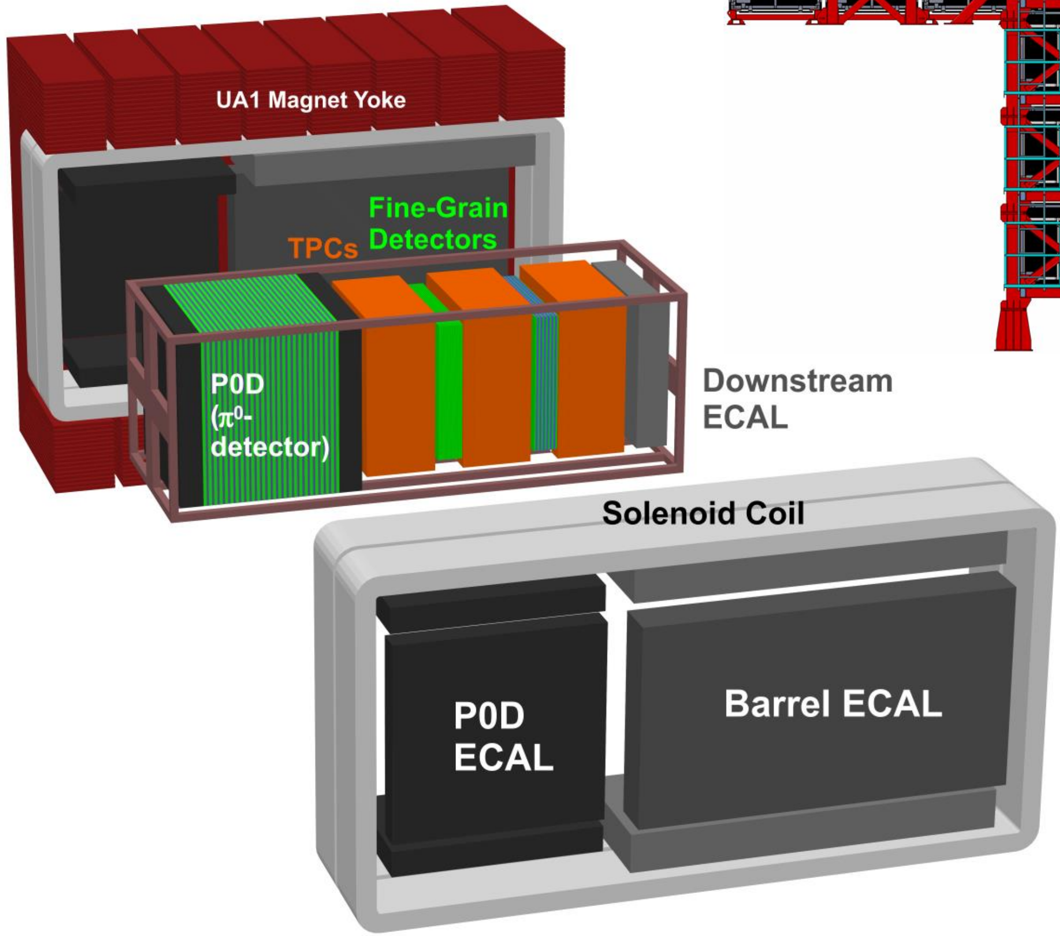


Near detectors



INGRID

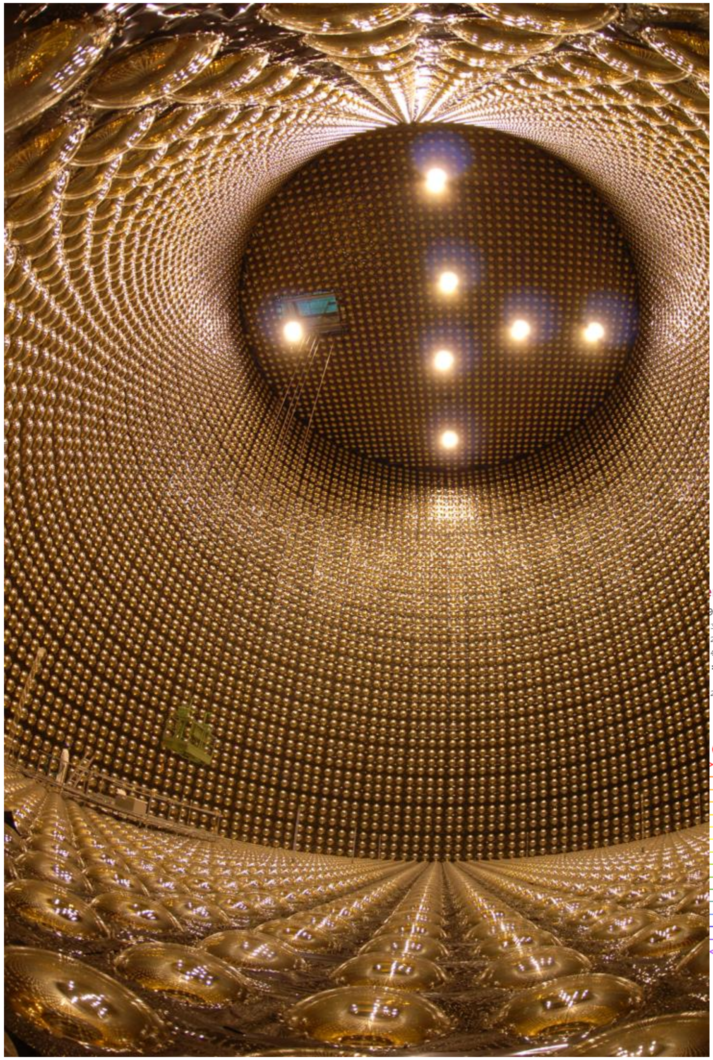
- Measure direction of neutrino beam
- Ensure stable beam operation (intensity, shape, direction)
- Tune neutrino flux prediction



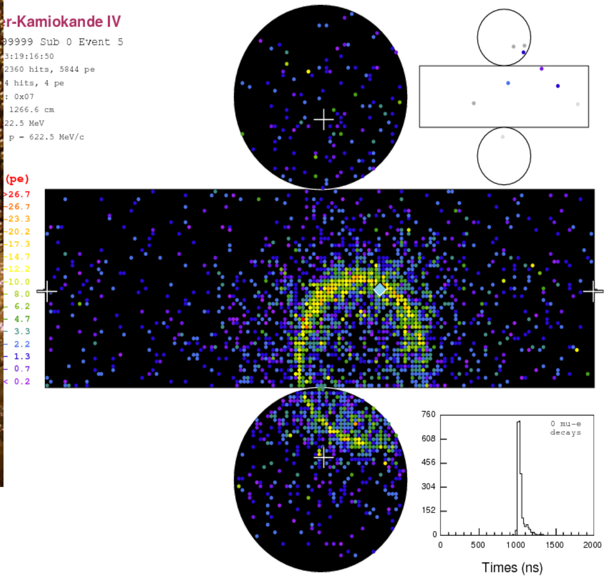
ND280

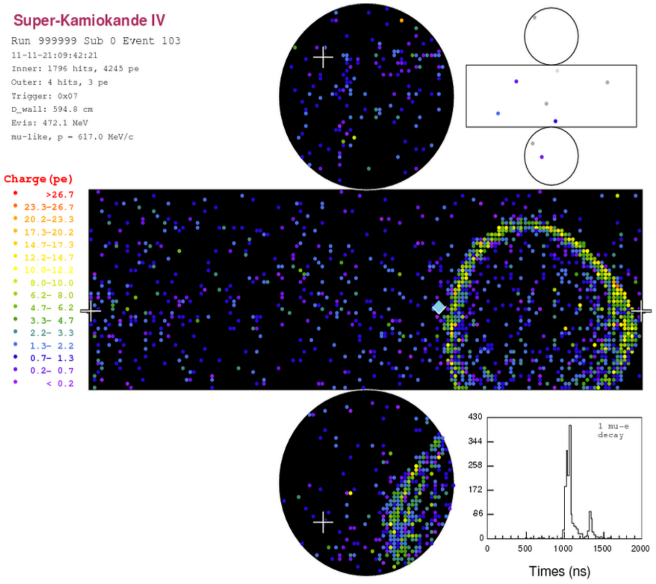
- Measure neutrino flux and cross section before oscillation
- UA1 magnet allows separation of neutrino and antineutrinos
- Oscillation analysis focuses on muon (anti-)neutrino samples

Super-Kamiokande



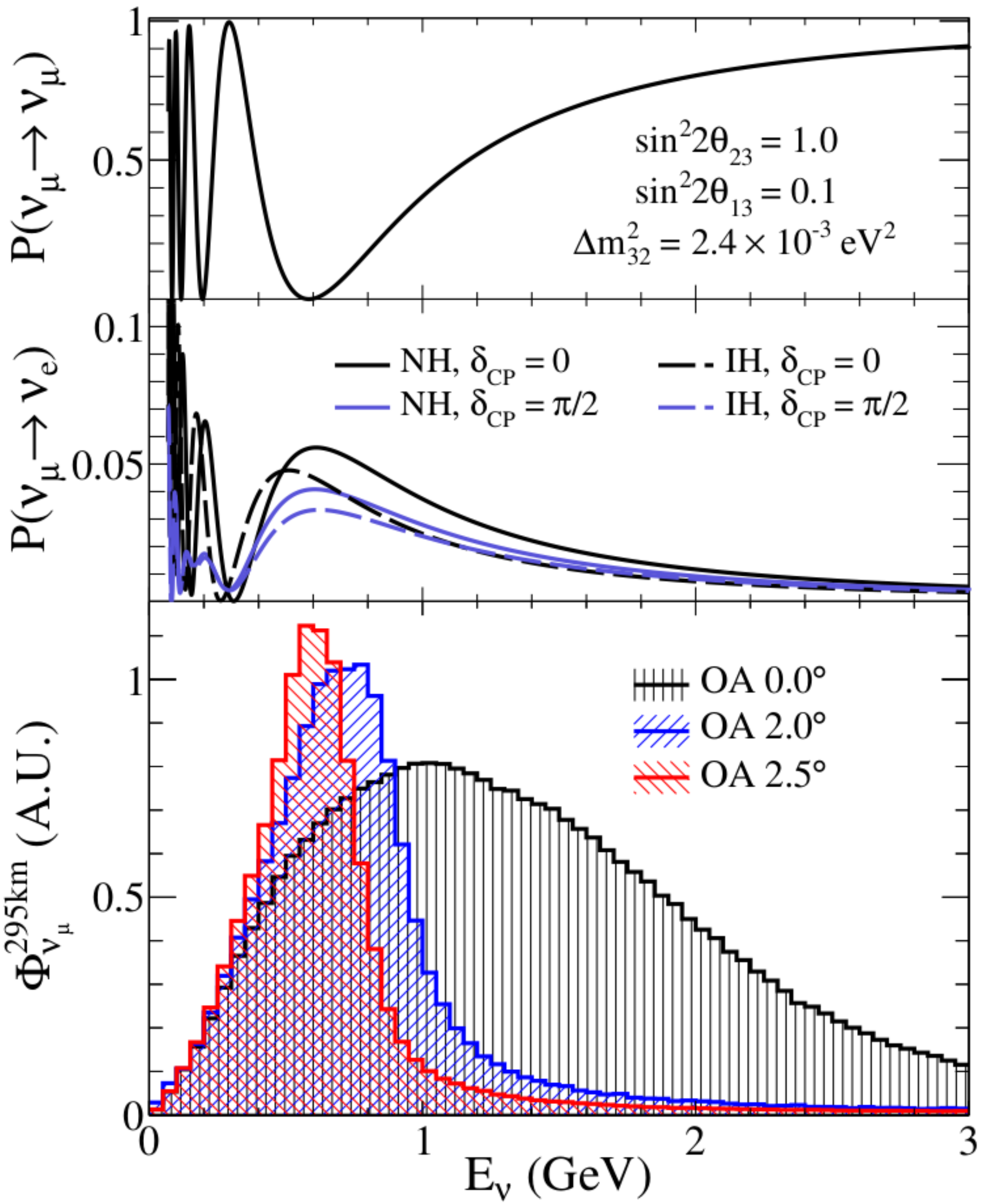
- 40,000 tons of ultra pure water
- 11,000 photo-multiplier tubes (PMTs)
- 1km overburden
- Separate electrons and muons by ring shape
  - Mis-ID <1%
  - No sign selection





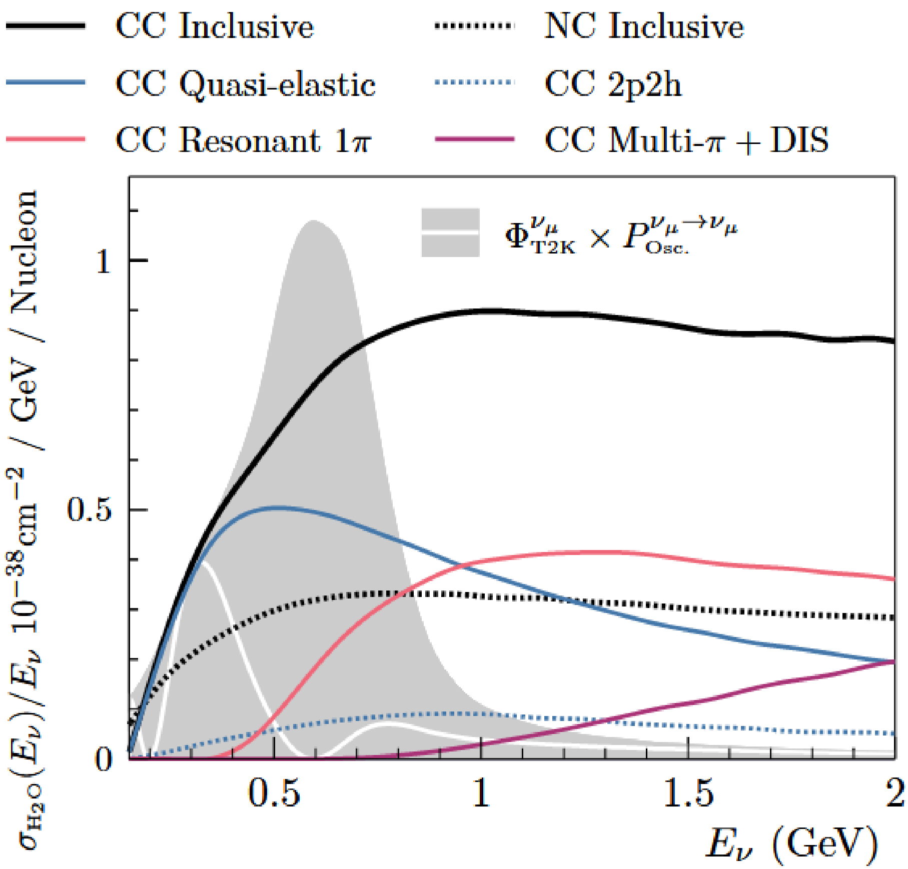
Off-axis beams

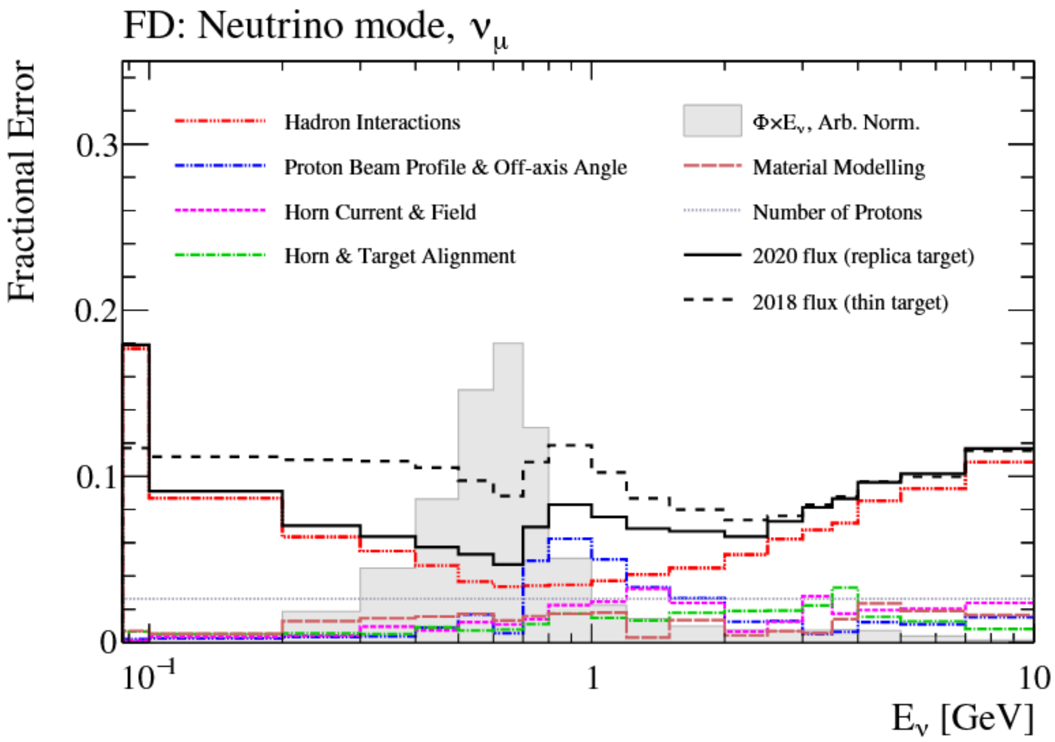
- Two-body pion decay
  - Angle and energy of neutrino directly linked
- Moving off axis:
  - Lower peak energy
  - Smaller high energy tail
  - Less energy spread
- T2K is at 2.5° off-axis



Flux and cross-section modelling

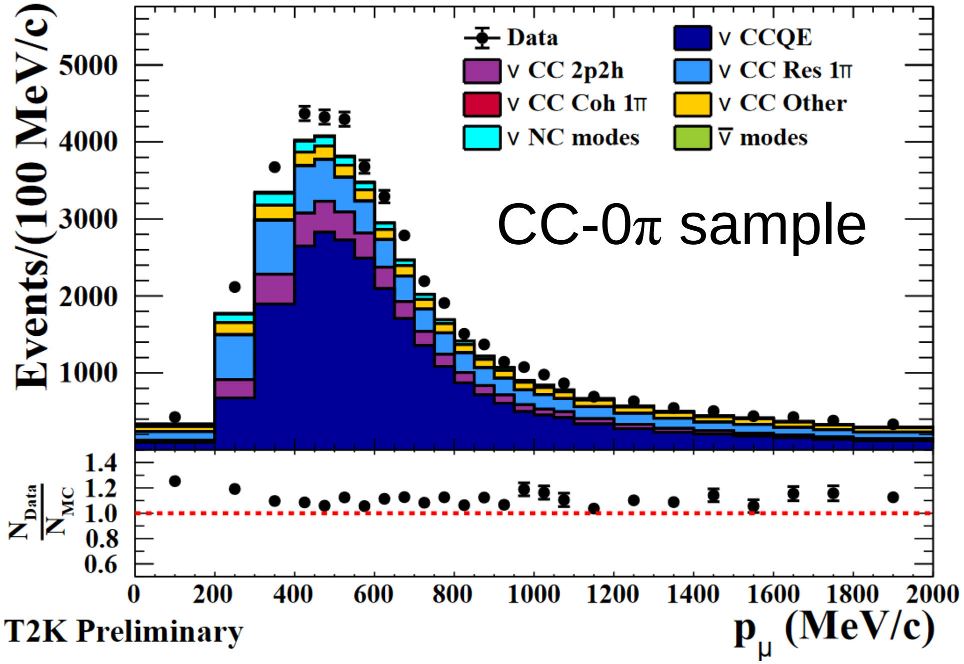
- T2K uses NEUT, 47 cross-section parameters in 2022 analysis
- Flux uncertainty binned as function of neutrino type, beam mode and energy

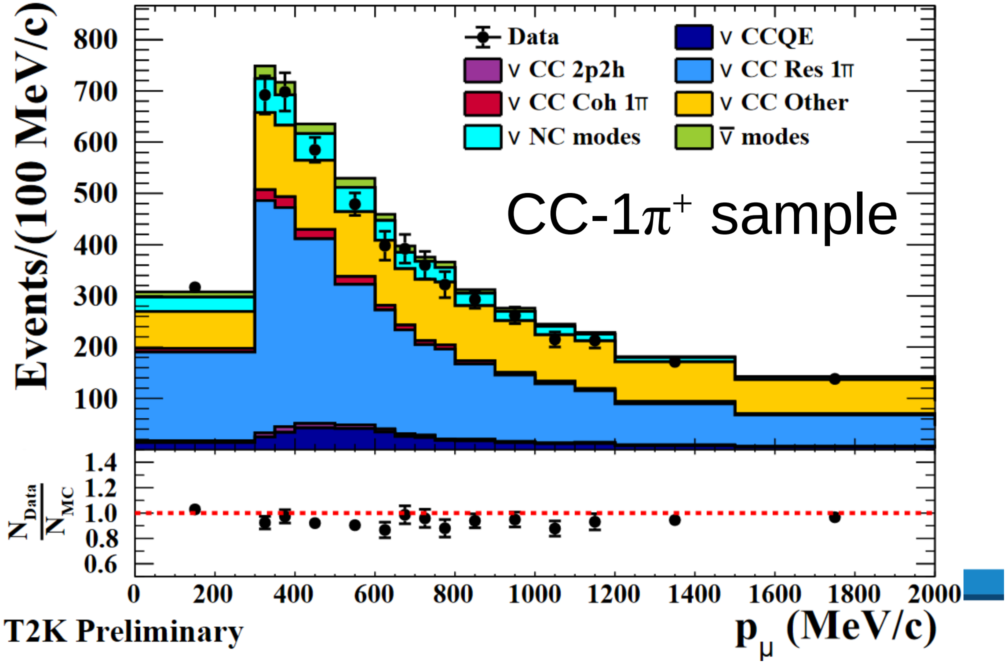


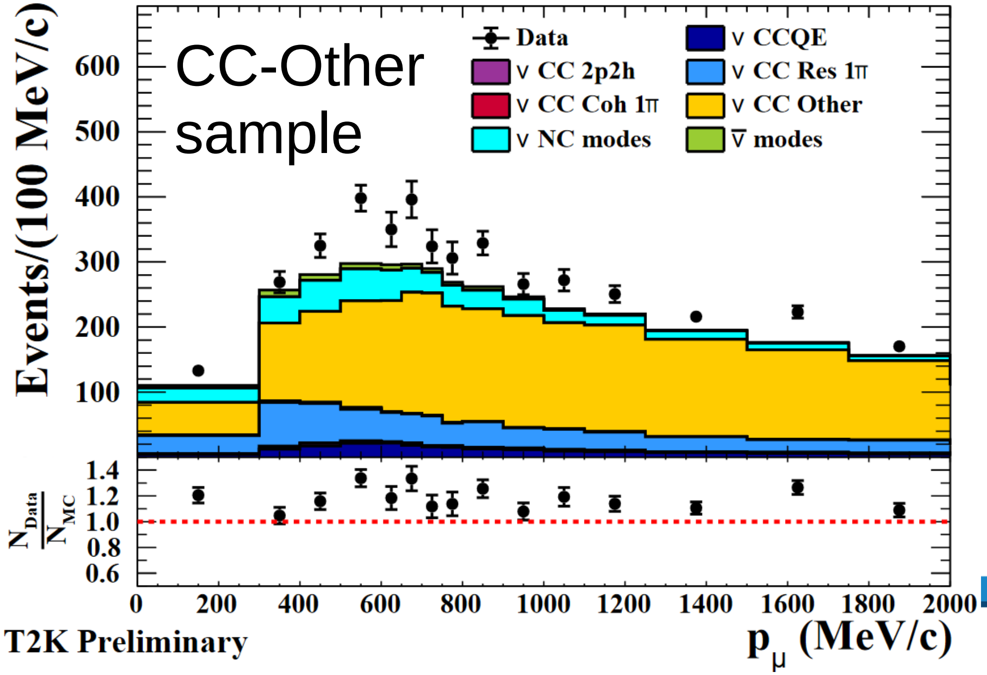


ND280 event samples

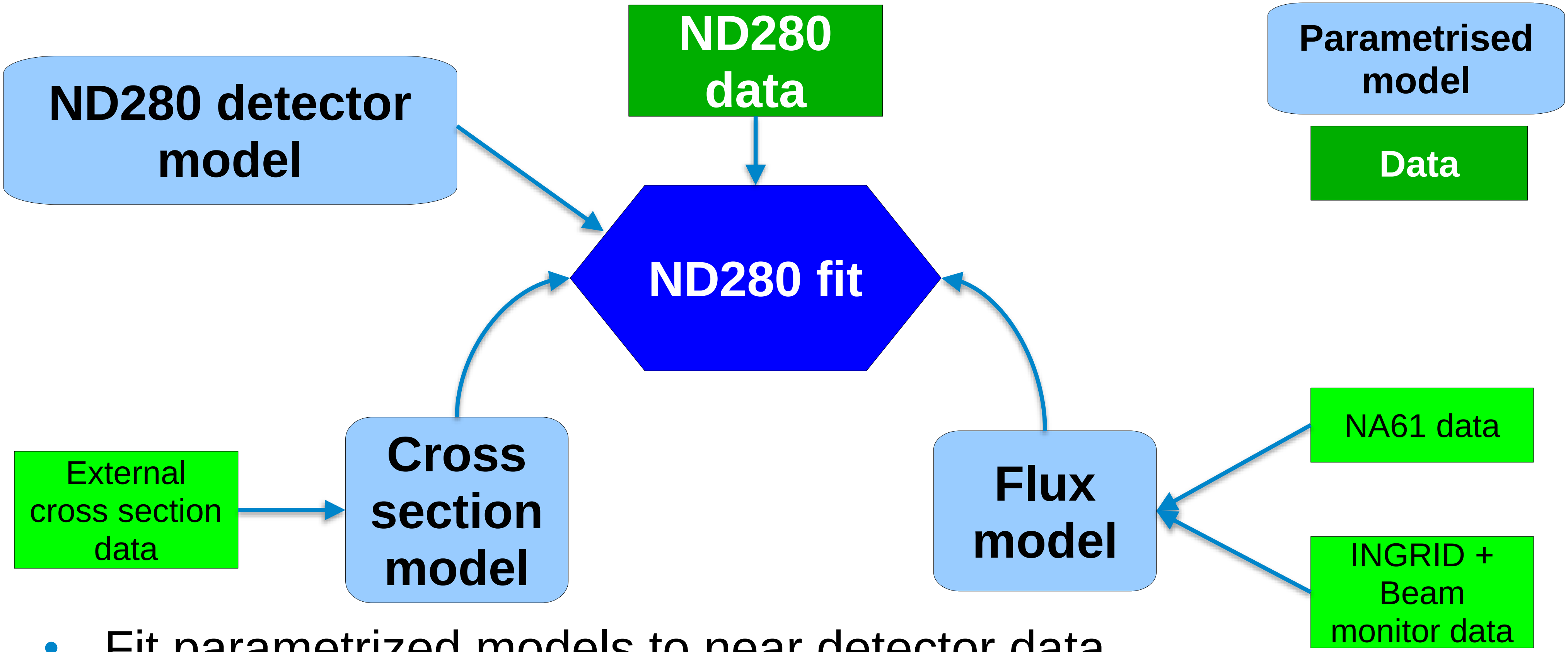
- Select highest momentum, muon-like, negative (positive) track as neutrino (antineutrino) candidate
- Count the number of tagged charged or neutral pions





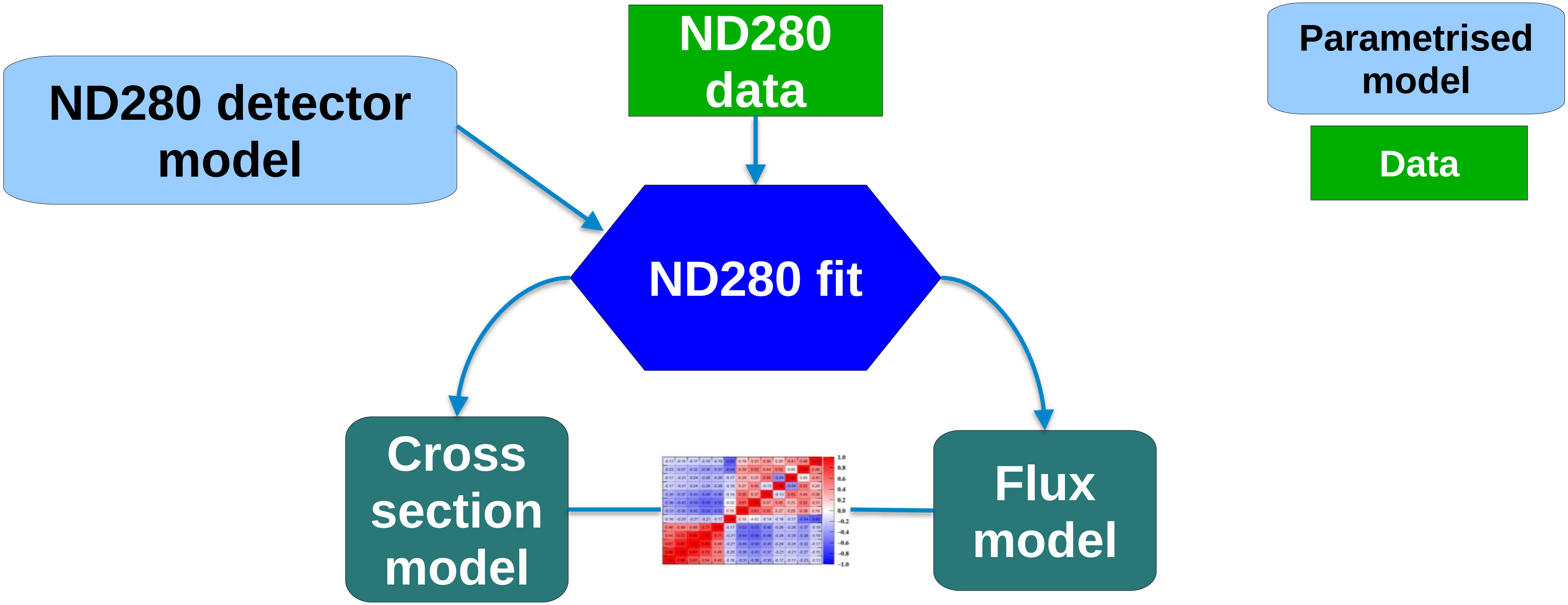


Near detector analysis



- Fit parametrized models to near detector data
  - Two separate analysis, Markov Chain MC and Minimisation, Bayesian and Frequentist methods

Near detector analysis

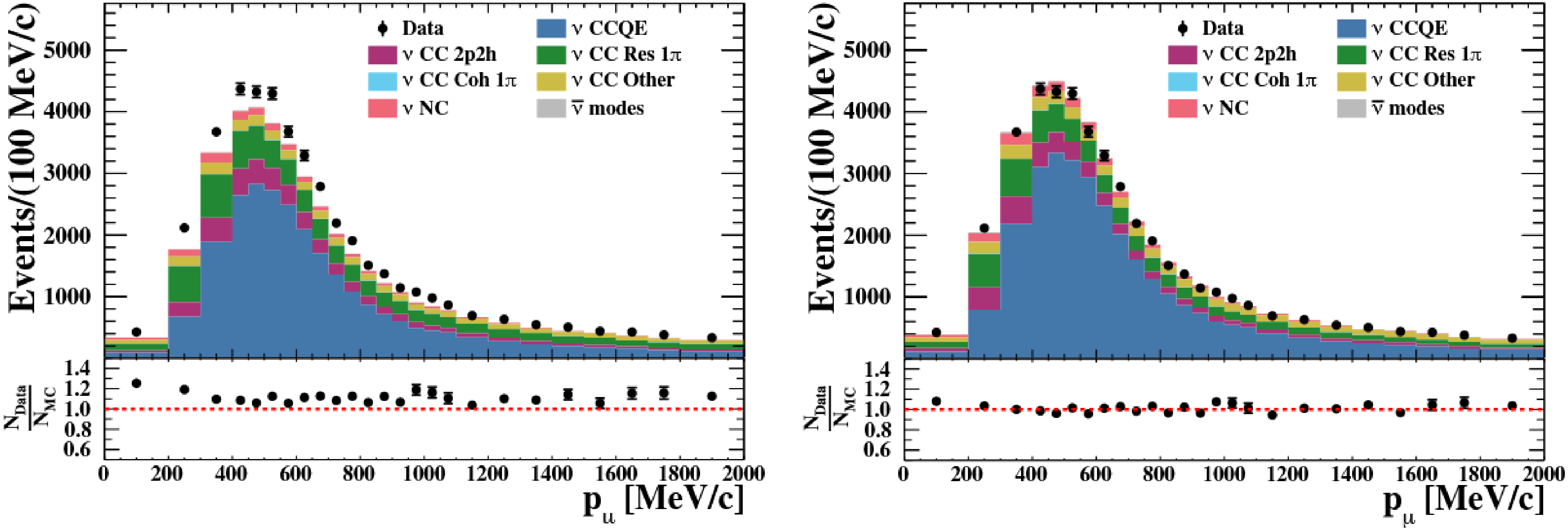


- Produces tuned flux and cross-section models
- Use models to predict unoscillated event rate at Super-K

Near detector fit

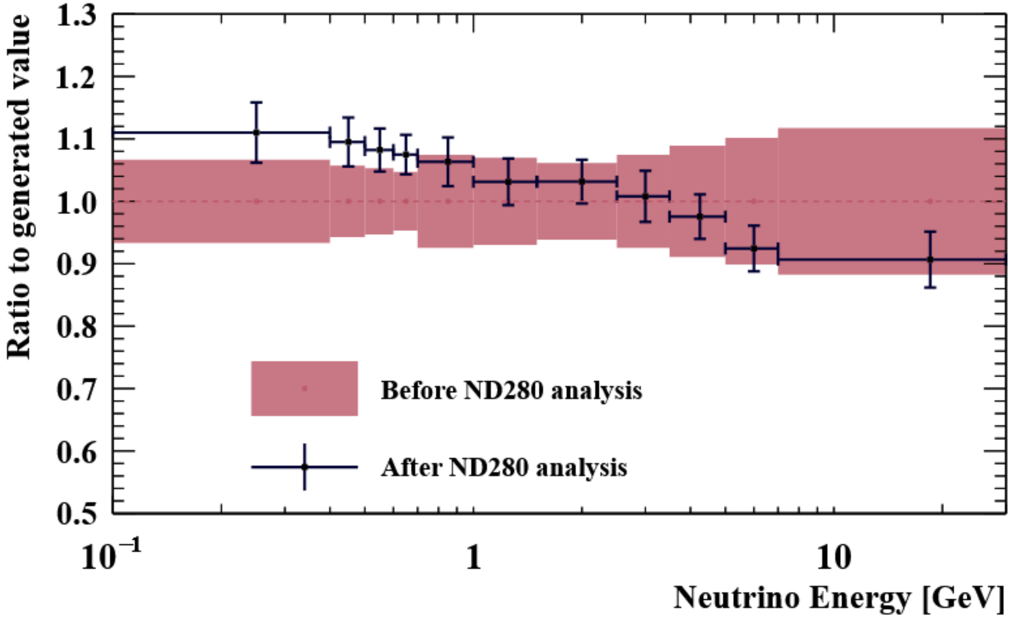
- Charged-current, zero-pion sample shown below
  - Prefit on left, postfit on right

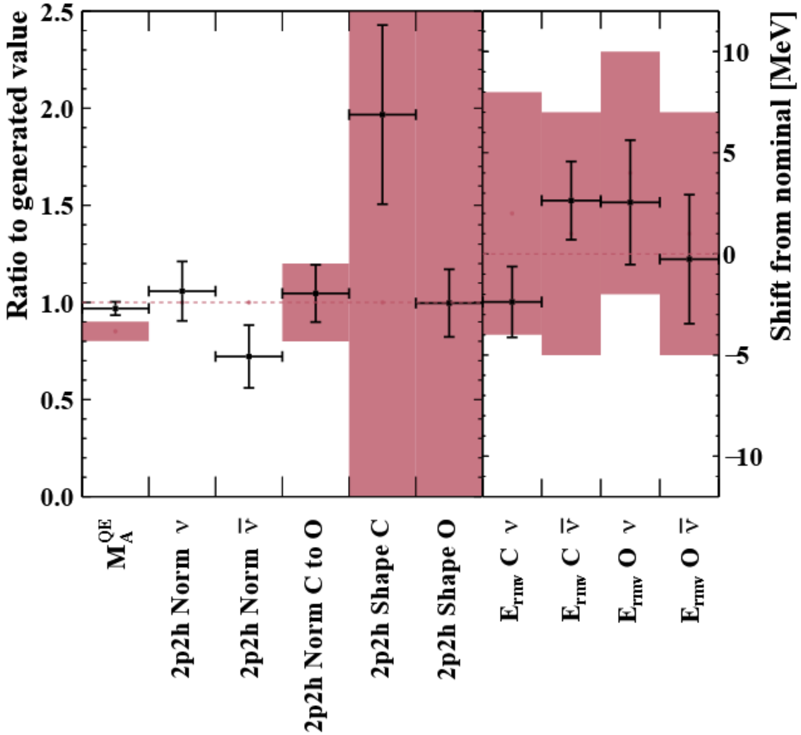
- MC about 10% too low prior to fit

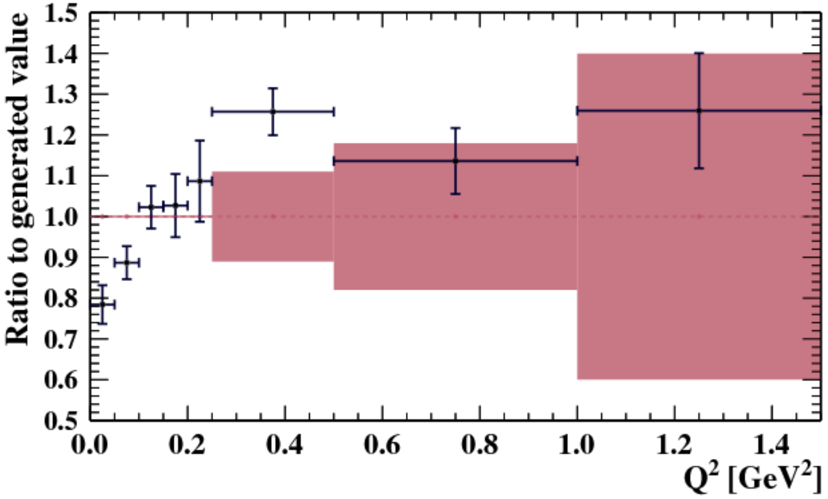


Near detector parameter results

- Tuned muon neutrino flux at Super-K shown right, some CCQE cross-section parameters below
  - Prior in red, fit result in black

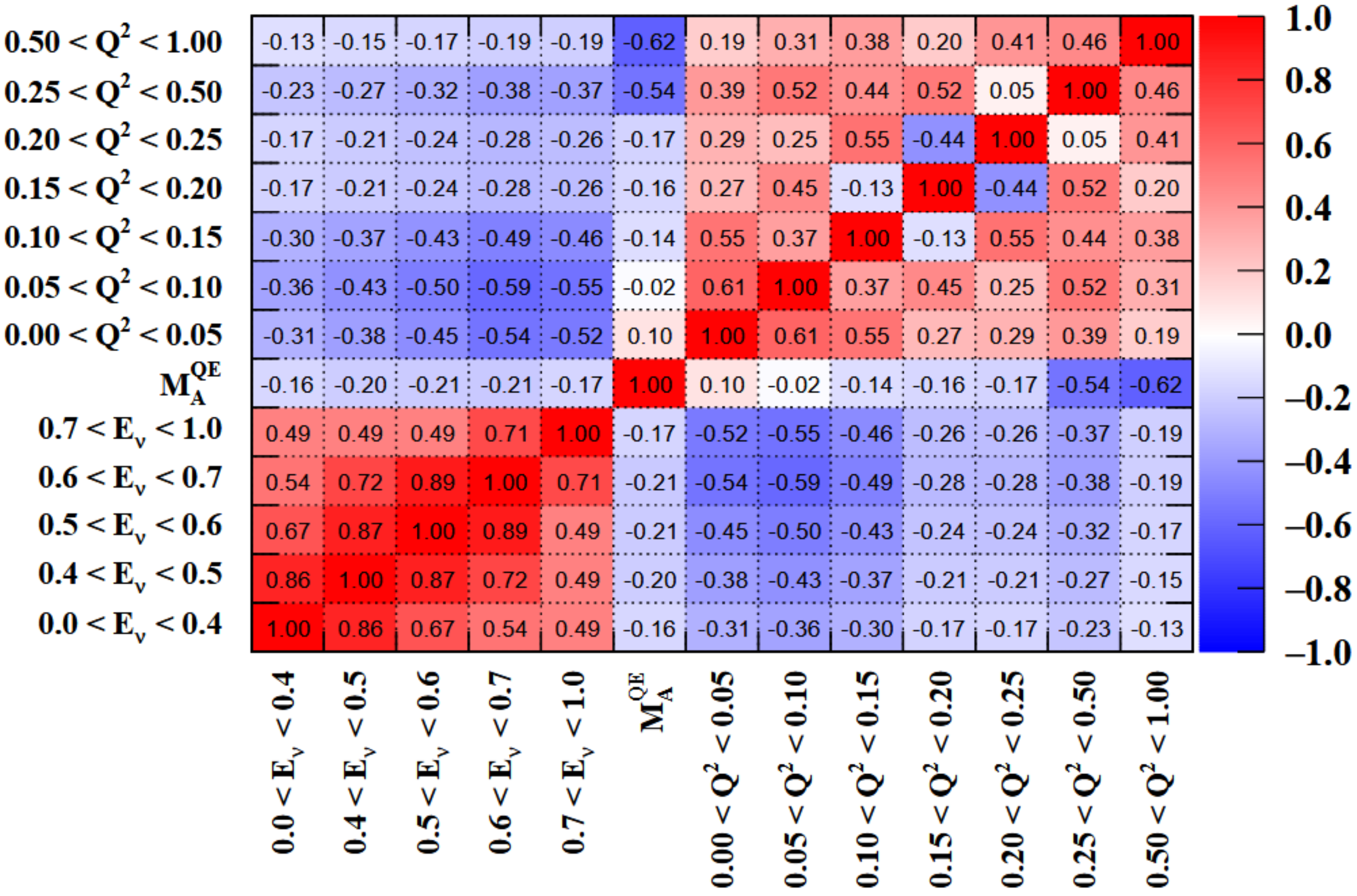






Event rate uncertainty

- Correlate neutrino flux (first 5 bins in this partial matrix) with neutrino cross section
- Reduces event rate uncertainty at SK
- Mis-modeling of cross section (flux) can impact flux (cross-section) parameters



	$0.0 < E_\nu < 0.4$	$0.4 < E_\nu < 0.5$	$0.5 < E_\nu < 0.6$	$0.6 < E_\nu < 0.7$	$0.7 < E_\nu < 1.0$	M_A^{QE}	$0.00 < Q^2 < 0.05$	$0.05 < Q^2 < 0.10$	$0.10 < Q^2 < 0.15$	$0.15 < Q^2 < 0.20$	$0.20 < Q^2 < 0.25$	$0.25 < Q^2 < 0.50$	$0.50 < Q^2 < 1.00$
$0.50 < Q^2 < 1.00$	-0.13	-0.15	-0.17	-0.19	-0.19	-0.62	0.19	0.31	0.38	0.20	0.41	0.46	1.00
$0.25 < Q^2 < 0.50$	-0.23	-0.27	-0.32	-0.38	-0.37	-0.54	0.39	0.52	0.44	0.52	0.05	1.00	0.46
$0.20 < Q^2 < 0.25$	-0.17	-0.21	-0.24	-0.28	-0.26	-0.17	0.29	0.25	0.55	-0.44	1.00	0.05	0.41
$0.15 < Q^2 < 0.20$	-0.17	-0.21	-0.24	-0.28	-0.26	-0.16	0.27	0.45	-0.13	1.00	-0.44	0.52	0.20
$0.10 < Q^2 < 0.15$	-0.30	-0.37	-0.43	-0.49	-0.46	-0.14	0.55	0.37	1.00	-0.13	0.55	0.44	0.38
$0.05 < Q^2 < 0.10$	-0.36	-0.43	-0.50	-0.59	-0.55	-0.02	0.61	1.00	0.37	0.45	0.25	0.52	0.31
$0.00 < Q^2 < 0.05$	-0.31	-0.38	-0.45	-0.54	-0.52	0.10	1.00	0.61	0.55	0.27	0.29	0.39	0.19
M_A^{QE}	-0.16	-0.20	-0.21	-0.21	-0.17	1.00	0.10	-0.02	-0.14	-0.16	-0.17	-0.54	-0.62
$0.7 < E_\nu < 1.0$	0.49	0.49	0.49	0.71	1.00	-0.17	-0.52	-0.55	-0.46	-0.26	-0.26	-0.37	-0.19
$0.6 < E_\nu < 0.7$	0.54	0.72	0.89	1.00	0.71	-0.21	-0.54	-0.59	-0.49	-0.28	-0.28	-0.38	-0.19
$0.5 < E_\nu < 0.6$	0.67	0.87	1.00	0.89	0.49	-0.21	-0.45	-0.50	-0.43	-0.24	-0.24	-0.32	-0.17
$0.4 < E_\nu < 0.5$	0.86	1.00	0.87	0.72	0.49	-0.20	-0.38	-0.43	-0.37	-0.21	-0.21	-0.27	-0.15
$0.0 < E_\nu < 0.4$	1.00	0.86	0.67	0.54	0.49	-0.16	-0.31	-0.36	-0.30	-0.17	-0.17	-0.23	-0.13

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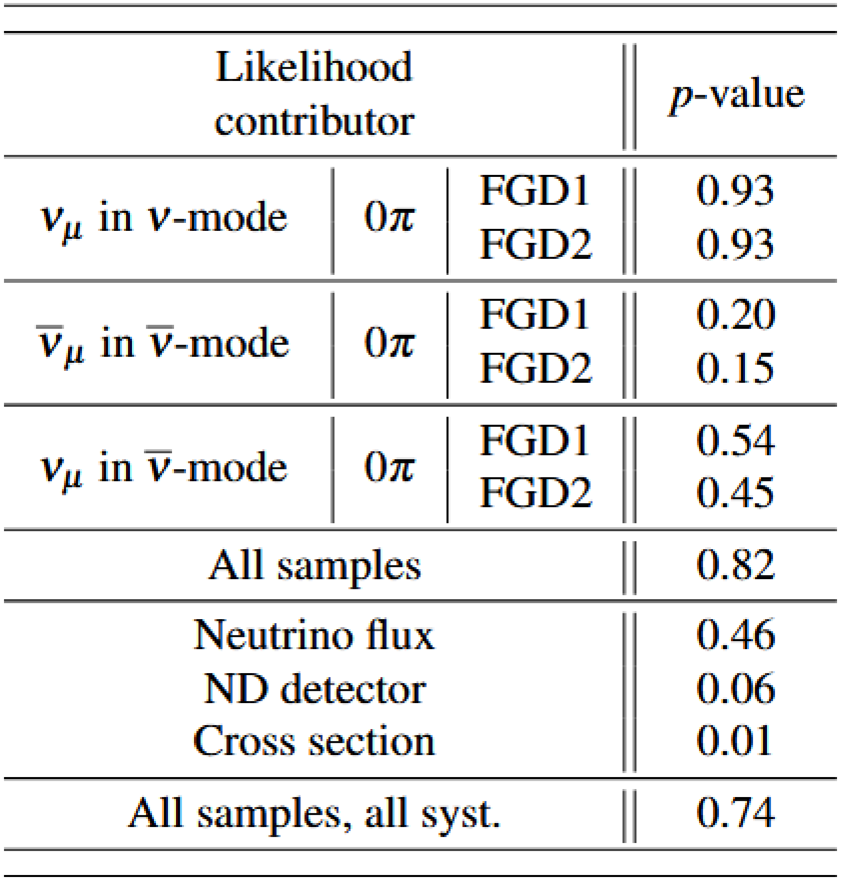
Near detector p-value

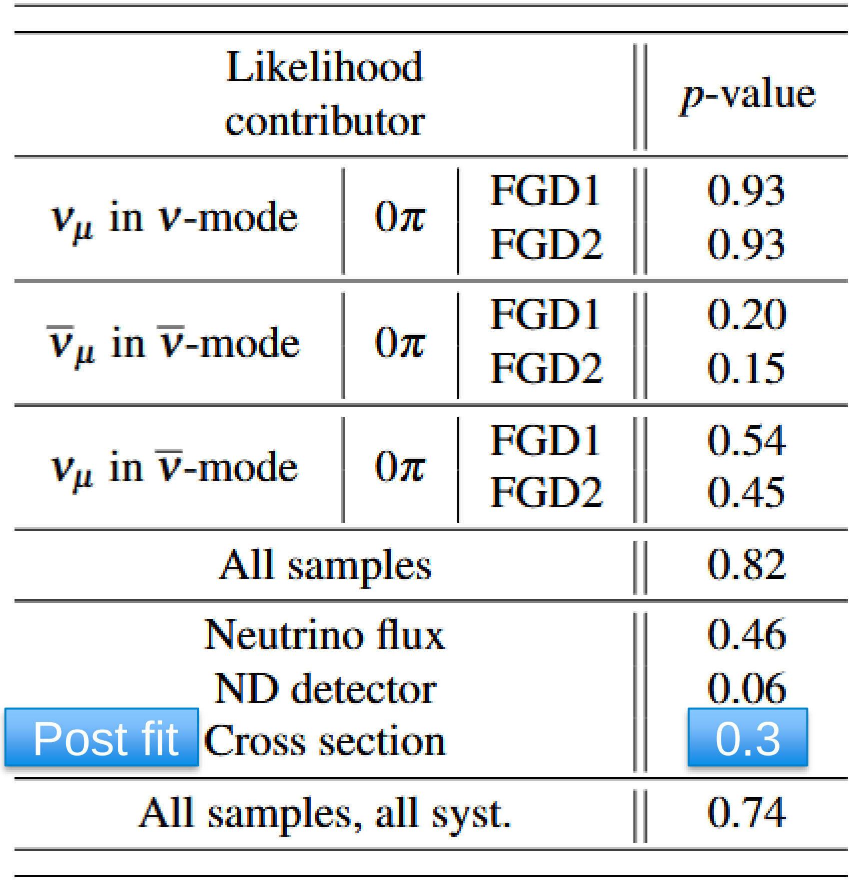
- Great, 74% probability of producing the observed data given our initial model!
- Ah, near detector systematics have a 6% probability, need some more work in future
- Oh no! Cross-section model has 1% probability of giving this data…



Likelihood contributor			p-value
ν_μ in ν-mode	0π	FGD1	0.93
		FGD2	0.93
$\overline{\nu}_\mu$ in $\overline{\nu}$-mode	0π	FGD1	0.20
		FGD2	0.15
ν_μ in $\overline{\nu}$-mode	0π	FGD1	0.54
		FGD2	0.45
All samples			0.82
Neutrino flux			0.46
ND detector			0.06
Cross section			0.01
All samples, all syst.			0.74

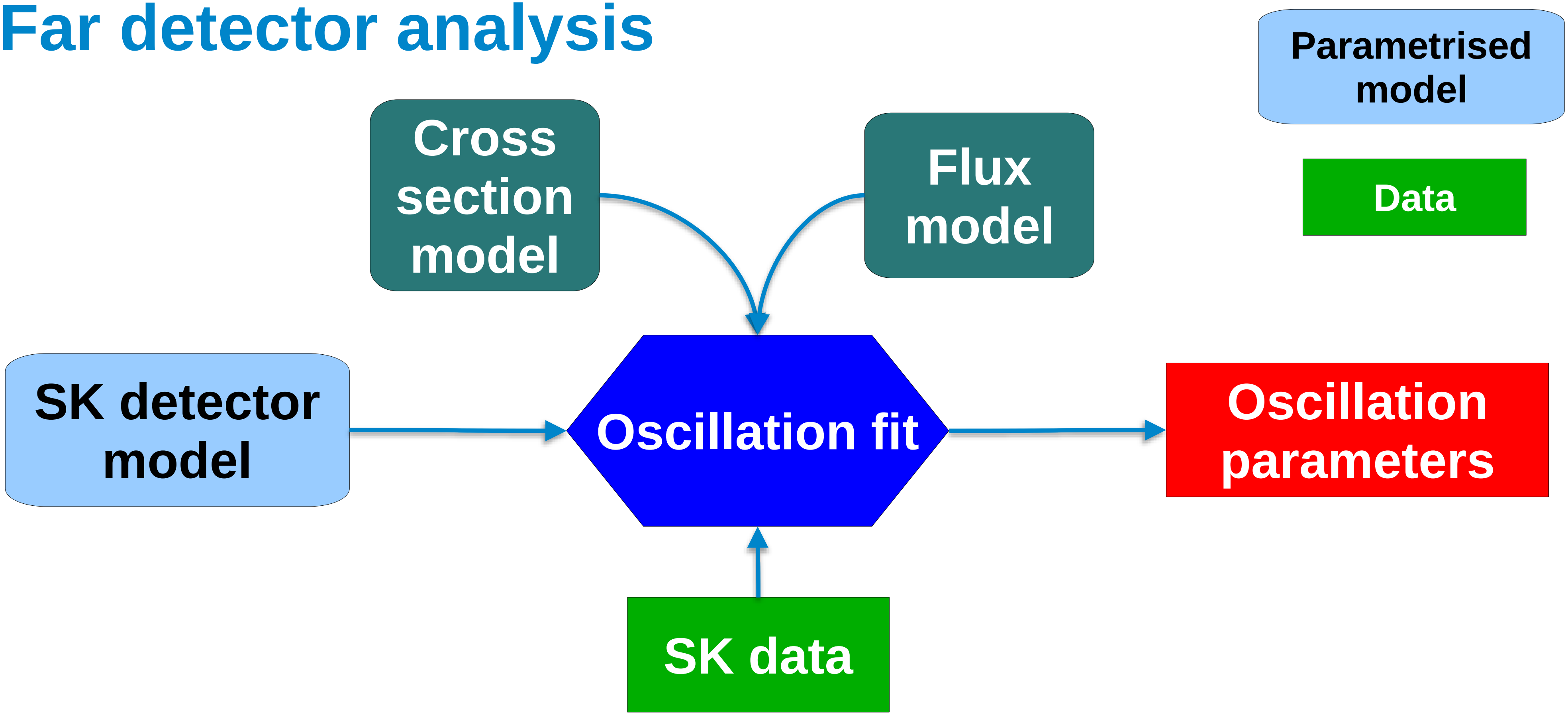
Near detector p-value

- Great, 74% probability of producing the observed data given our initial model!
- Ah, near detector systematics have a 6% probability, need some more work in future
- Oh no! Cross-section model has 1% probability of giving this data…
  - Largely from pull on MaQE, MaRES and CA5
- But the postfit model agrees reasonably with the data



Likelihood contributor			*p*-value
ν_μ in ν-mode	0π	FGD1	0.93
		FGD2	0.93
$\bar{\nu}_\mu$ in $\bar{\nu}$-mode	0π	FGD1	0.20
		FGD2	0.15
ν_μ in $\bar{\nu}$-mode	0π	FGD1	0.54
		FGD2	0.45
All samples			0.82
Neutrino flux			0.46
ND detector			0.06
Post fit Cross section			0.3
All samples, all syst.			0.74

Far detector analysis



Parametrised model

Data

Cross section model

Flux model

SK detector model

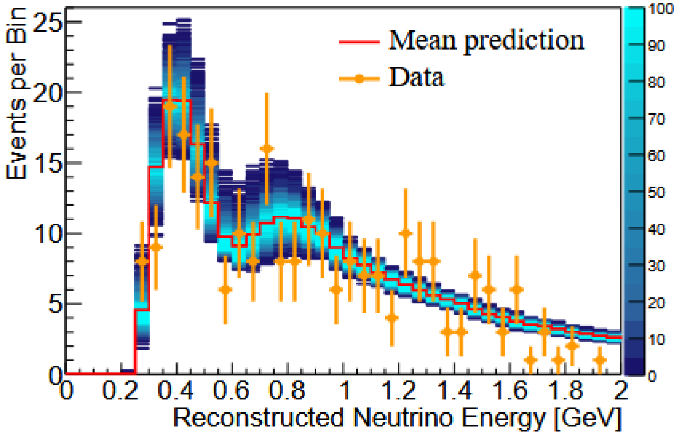
Oscillation fit

Oscillation parameters

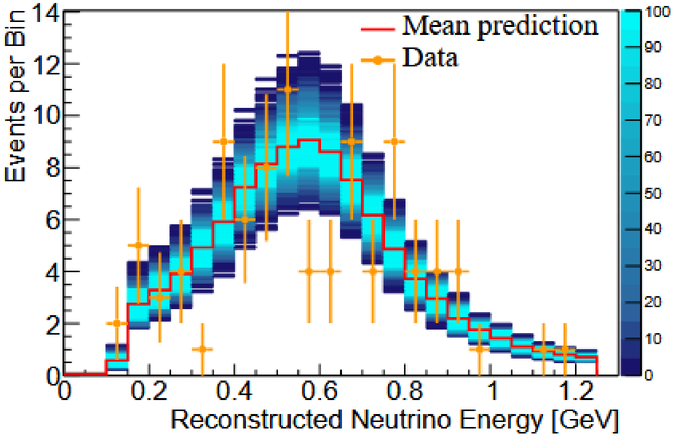
SK data

- Apply oscillation parameters to prediction from tuned models
- Fit to data, marginalizing over nuisance parameters
  - MaCh3 does combined fit of ND + FD, but in principle is ~same process

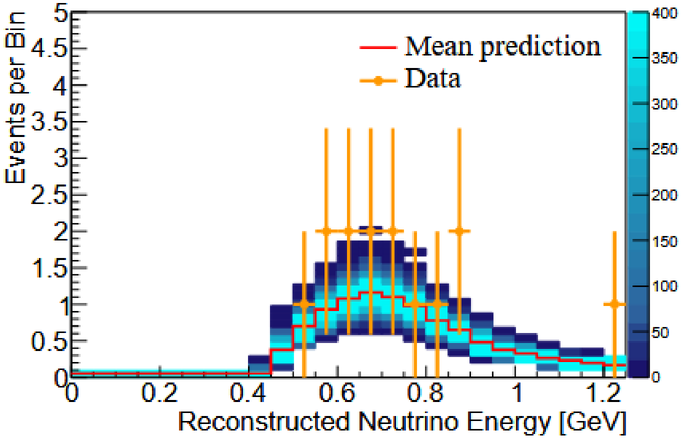
Far detector prediction and data



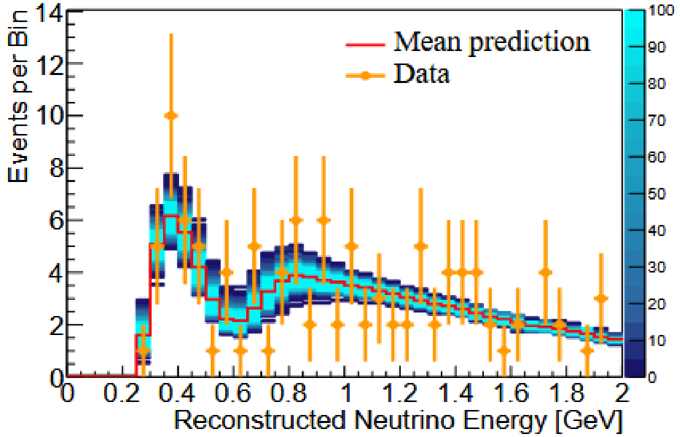
(a) ν-mode 1Rμ



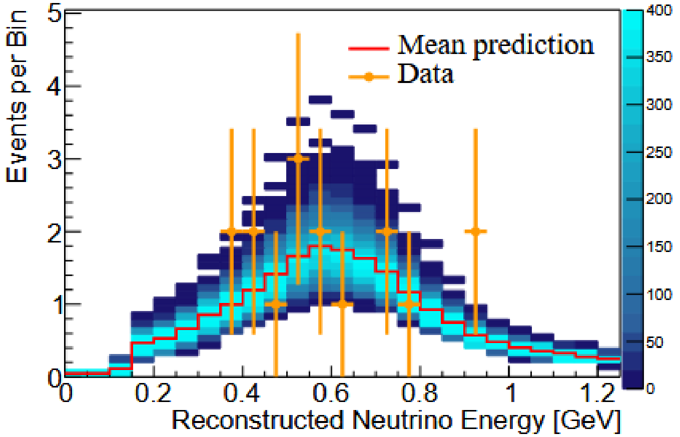
(b) ν-mode 1Re



(c) ν-mode 1Re1de

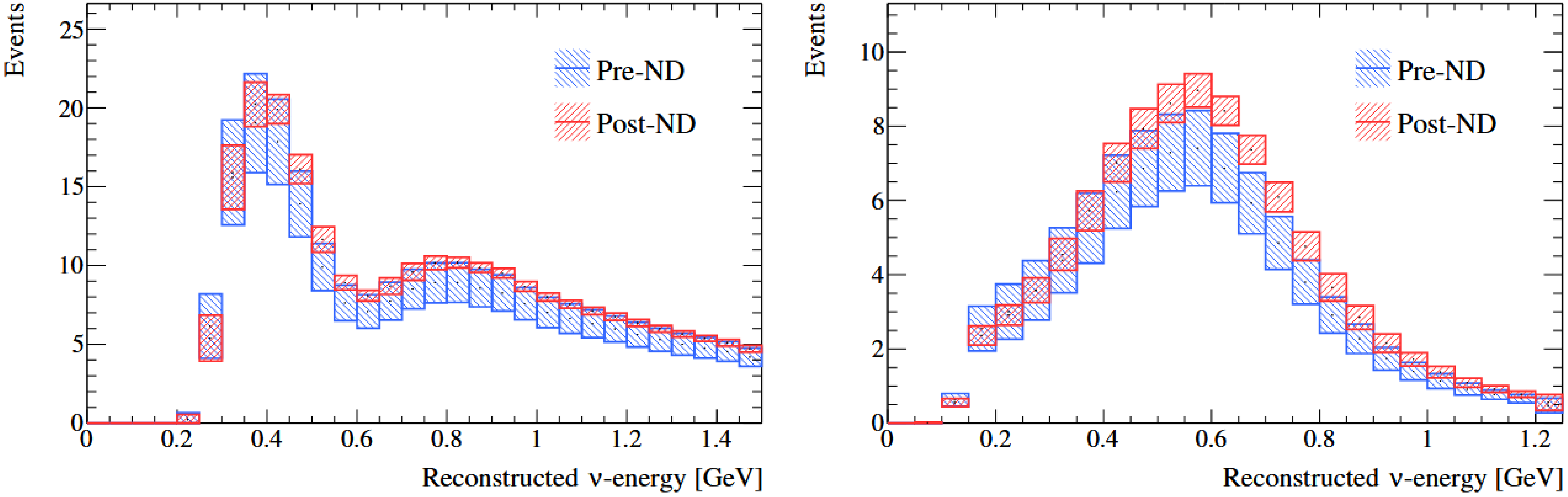


(d) $\overline{\nu}$-mode 1Rμ



(e) $\overline{\nu}$-mode 1Re

Effect of near detector fit on SK prediction

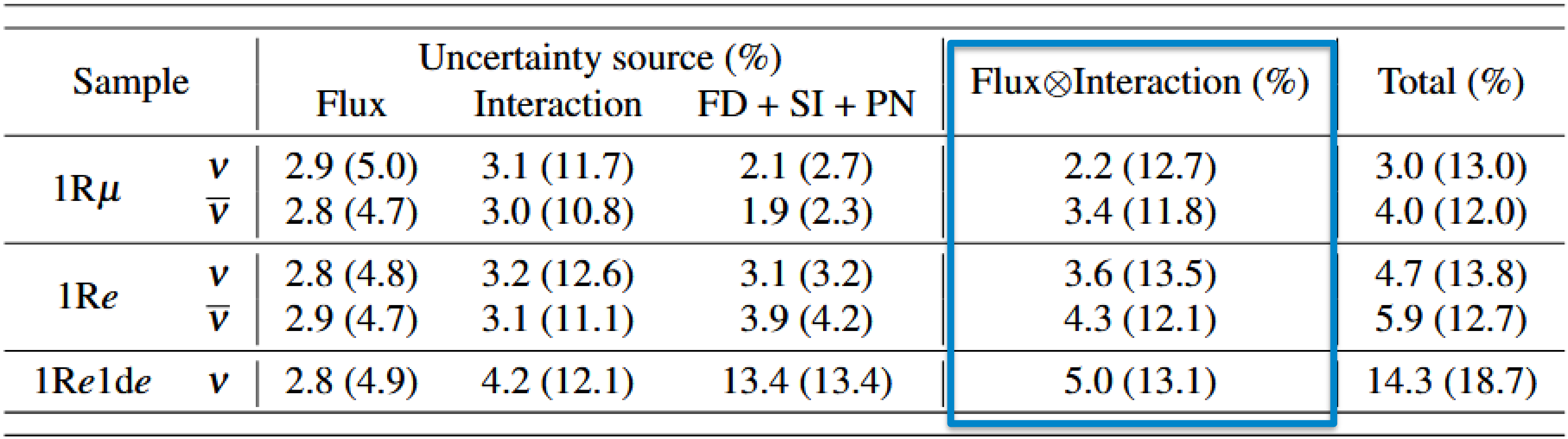


(a) ν-mode 1Rμ

(b) ν-mode 1Re

- Far detector single ring, muon-like sample on left, single ring electron-like sample on right
- ND280 fit result (red) increases predicted event rate, changes shape of spectrum and reduces systematic uncertainty

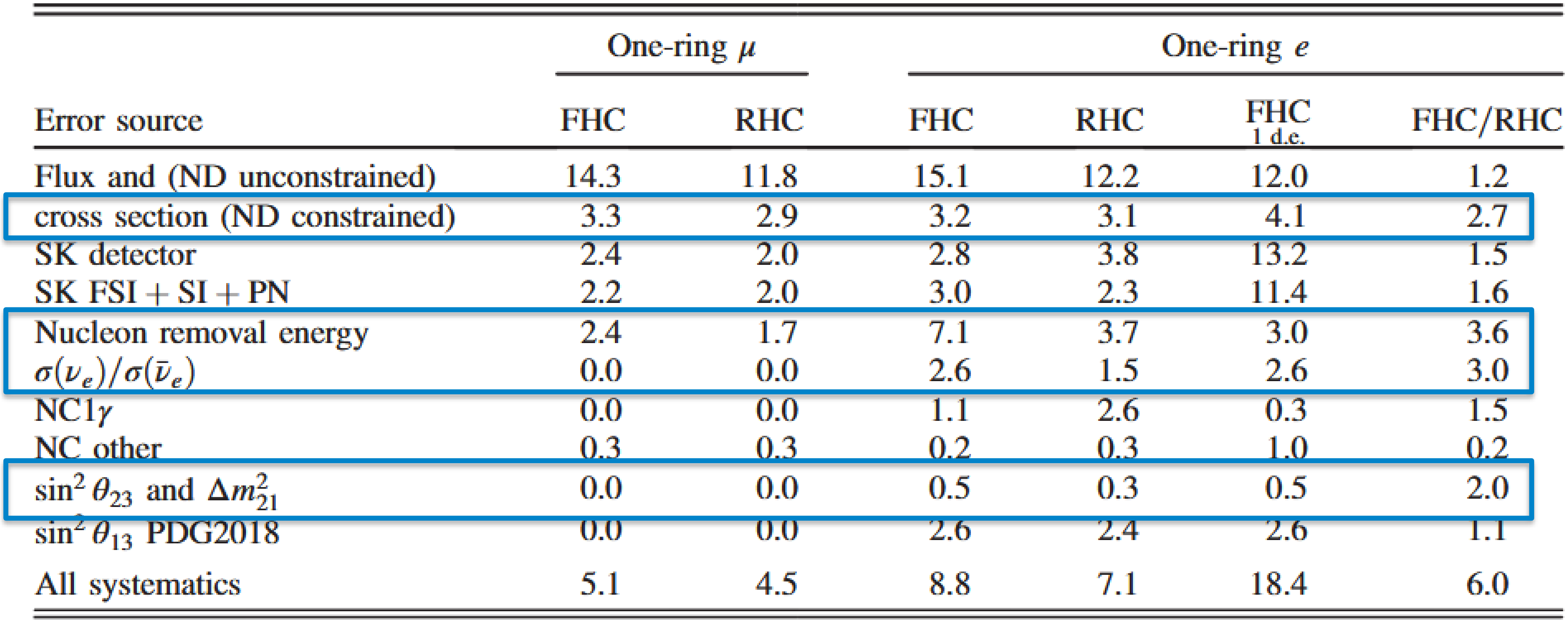
T2K systematic errors



Sample		Uncertainty source (%)			Flux⊗Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

- Uncertainty on predicted SK event rate after ND280 fit
  - Flux and cross-section uncertainties are correlated so the combination gives a smaller uncertainty than the individual parts

T2K systematic errors (2020)



	One-ring μ		One-ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
SK detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI + SI + PN	2.2	2.0	3.0	2.3	11.4	1.6
Nucleon removal energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All systematics	5.1	4.5	8.8	7.1	18.4	6.0

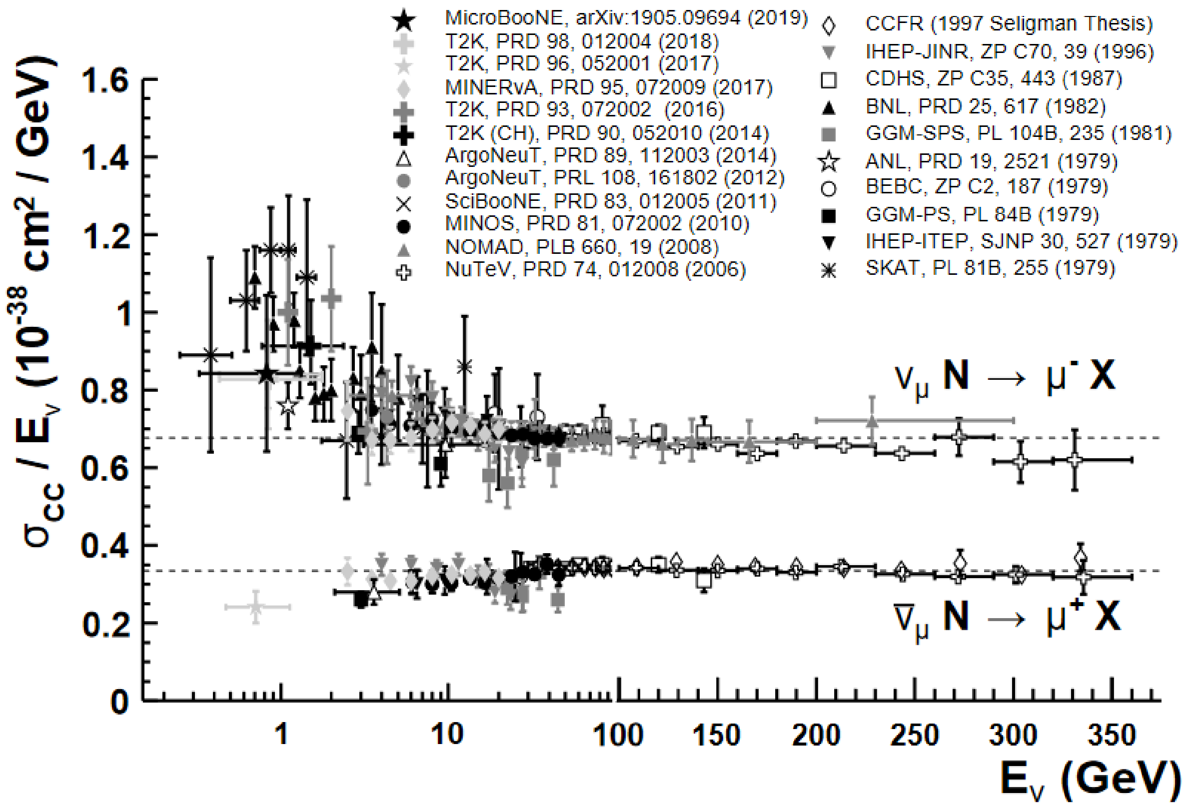
PhysRevD.103.112008

- Final column is “CP-violating” systematic error
  - Nucleon removal energy discussed later, fixed in 2022 analysis
  - ND constrained rate error can be reduced
  - Electron neutrino cross-section more difficult to reduce – target for next gen
  - Disappearance parameters also a leading error term

Robustness checks

Neutrino cross section model uncertainty

- World data is imprecise below ~10 GeV neutrino energy
- Multiple, plausible models exist, however:
  - T2K analysis based on a single model



G. Zeller, PDG Neutrino Cross Sections 2019

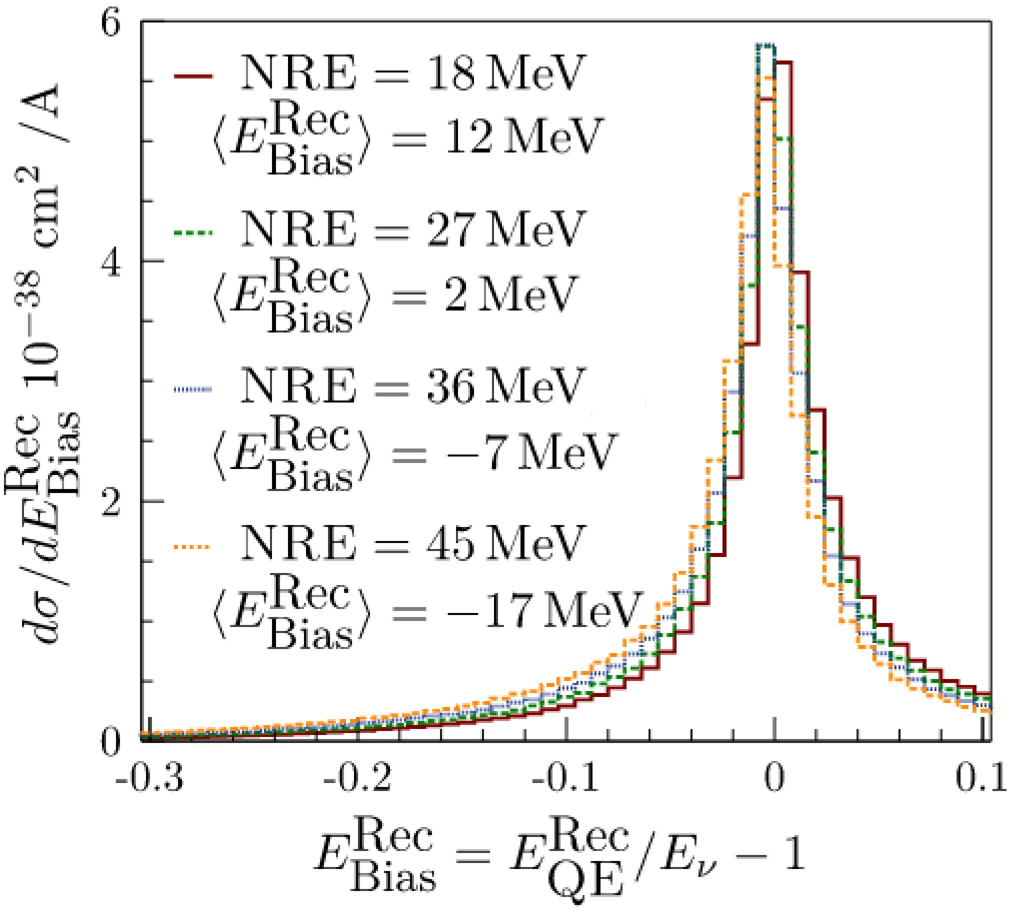
Simulated data studies

- Use information about simulated interactions to produce mock data based on a different neutrino interaction model
    - Detailed description can be found here: https://arxiv.org/pdf/2303.03222.pdf

- Pass mock data through near and far detector fitters
    - Tune nominal interaction model to try and match mock data model
    - Extract oscillation parameter contours and compare to our expectation
    - Use results to add additional uncertainties to oscillation contours from real data fit

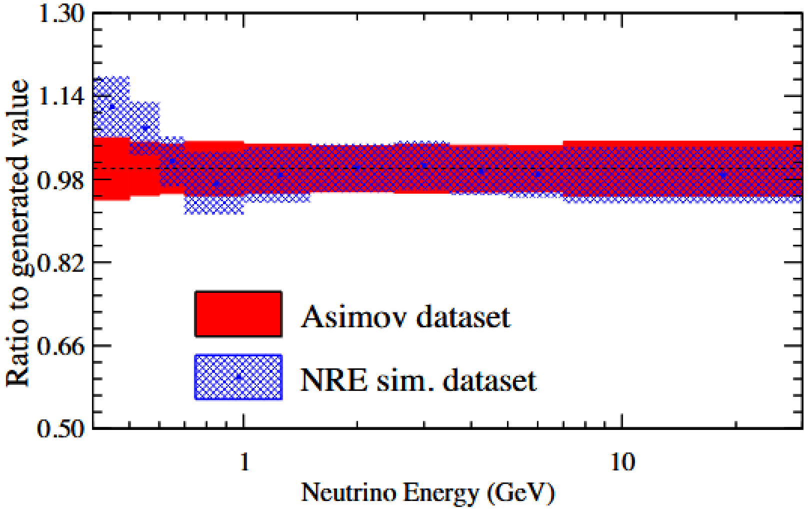
Example from 2020: Nucleon Removal Energy

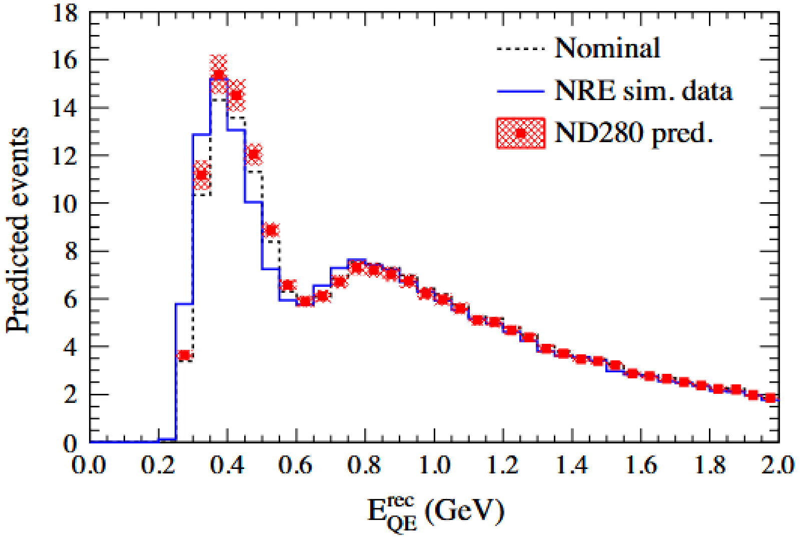
- Energy required to liberate nucleon from nucleus depends on the nuclear model
    - Global Relativistic Fermi Gas (RFG)
    - Local RFG
    - Spectral function
    - Etc.
- Simulate differences and model by shifting lepton momentum
    - Introduces energy bias (<3%) to SK reconstruction

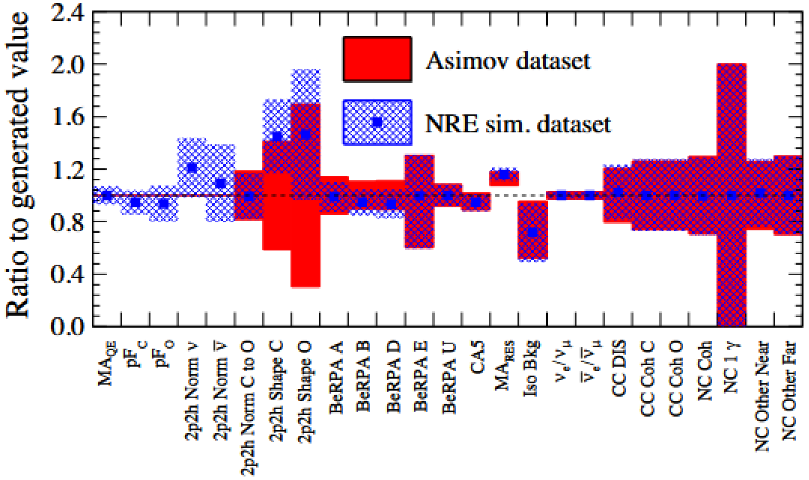


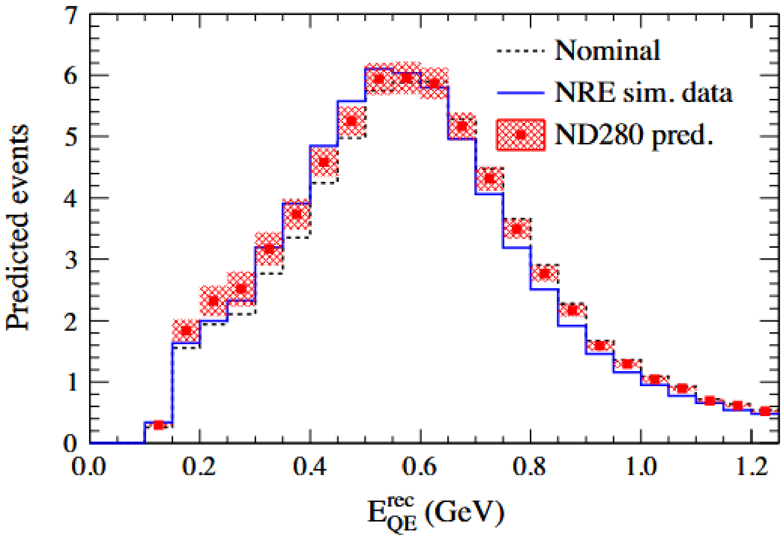
PhysRevD.103.112008

Nucleon Removal Energy at ND280



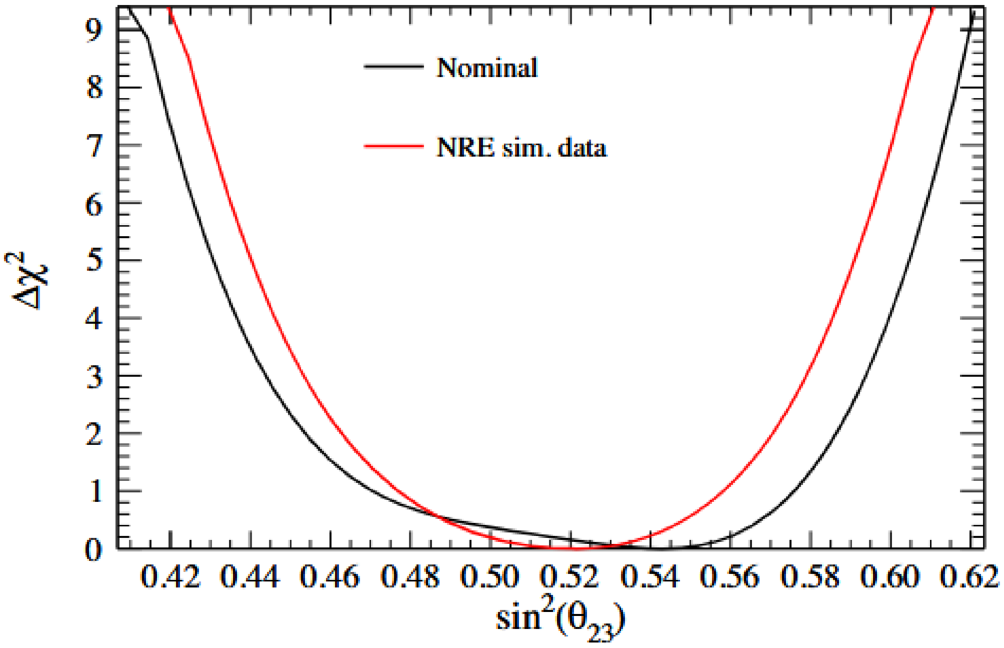


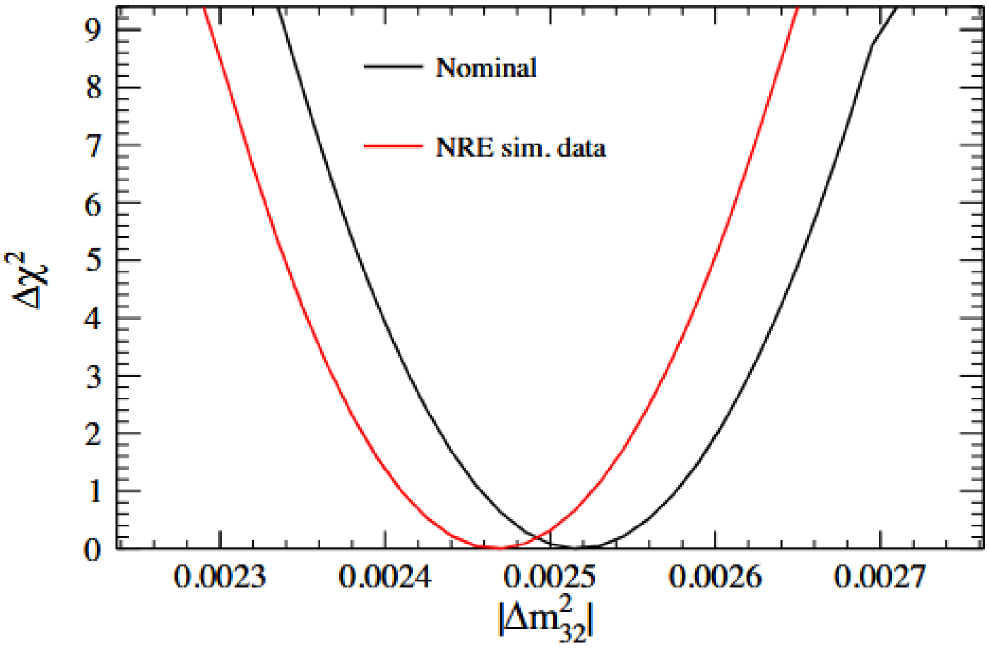




PhysRevD.103.112008

Nucleon Removal Energy results



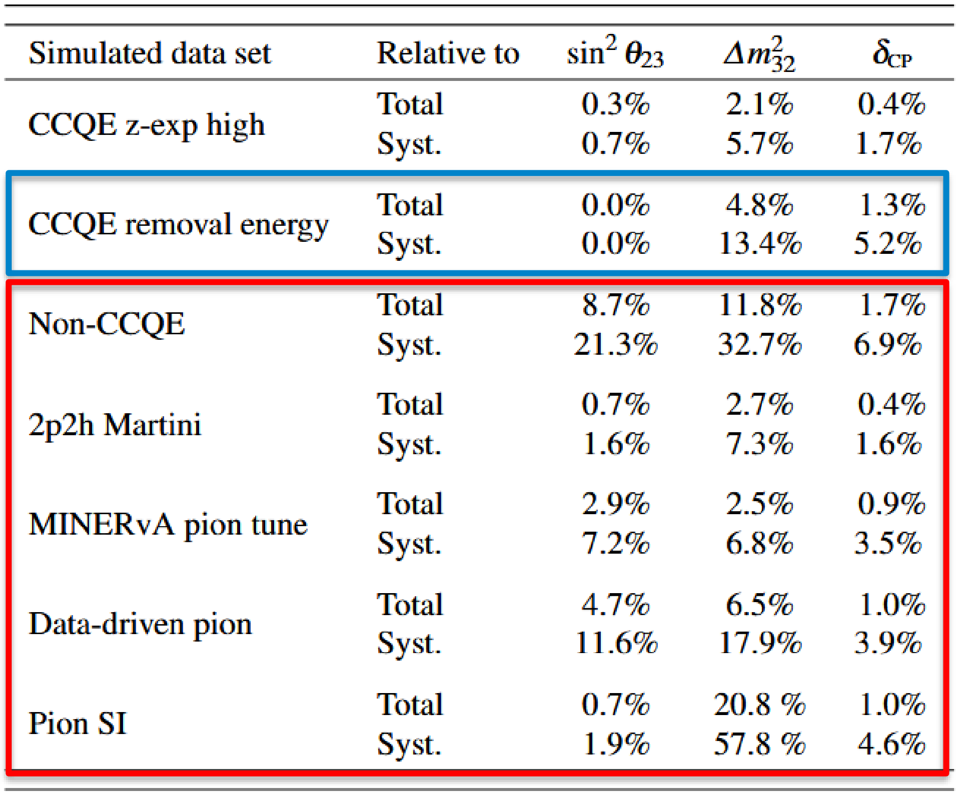


- See large shift in best fit point for $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$
- Look at shift in centre of 1σ allowed region and compare to size of systematic uncertainty
- Also check whether the change in the δ_{CP} likelihood surface would alter outcome of δ_{CP} exclusion

PhysRevD.103.112008

Simulated data studies in 2022

- Removal energy treatment improved for 2022 analysis
- Model uncertainties can be >50% of current systematics budget
- For DUNE and HK systematic and statistical error will be smaller
  - Impact of model uncertainties will grow



Simulated data set	Relative to	$\sin^2\theta_{23}$	Δm^2_{32}	δ_{CP}
CCQE z-exp high	Total	0.3%	2.1%	0.4%
	Syst.	0.7%	5.7%	1.7%
CCQE removal energy	Total	0.0%	4.8%	1.3%
	Syst.	0.0%	13.4%	5.2%
Non-CCQE	Total	8.7%	11.8%	1.7%
	Syst.	21.3%	32.7%	6.9%
2p2h Martini	Total	0.7%	2.7%	0.4%
	Syst.	1.6%	7.3%	1.6%
MINERvA pion tune	Total	2.9%	2.5%	0.9%
	Syst.	7.2%	6.8%	3.5%
Data-driven pion	Total	4.7%	6.5%	1.0%
	Syst.	11.6%	17.9%	3.9%
Pion SI	Total	0.7%	20.8 %	1.0%
	Syst.	1.9%	57.8 %	4.6%

Tab. 15: Biases on the main oscillation parameters for each simulated data set, calculated as the shift in the middle of the 1σ confidence interval relative to the overall uncertainty from systematic sources ("Syst.") and the total ("Total") to one decimal place.

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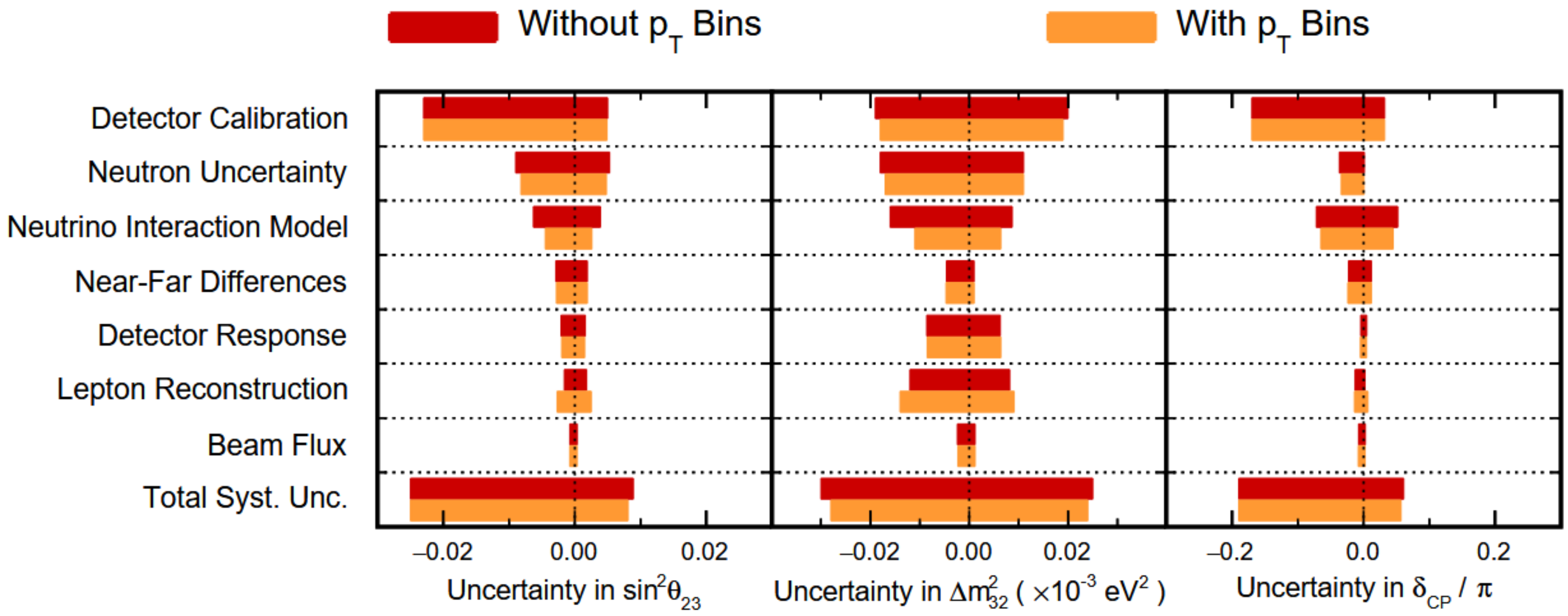
A note on NOvA

https://arxiv.org/pdf/2108.08219.pdf



- Functionally identical near and far detector
- Neutrino interaction model and beam flux uncertainties significantly reduced
- Detector response/reconstruction more important

Looking towards future near detectors

What does a near detector need to do?

- Need to predict unoscillated event rate at far detector with minimal bias and maximum precision

$$N_{obs} = \Phi(E_\nu, \nu, \boldsymbol{\theta}) \times \sigma(E_\nu, \nu) \times \epsilon(\text{Detector}, E_\nu, \sigma) \times P_{\nu_x \to \nu_y}(\boldsymbol{\theta})$$

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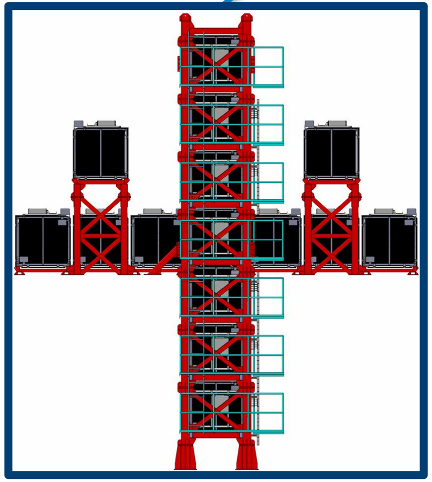
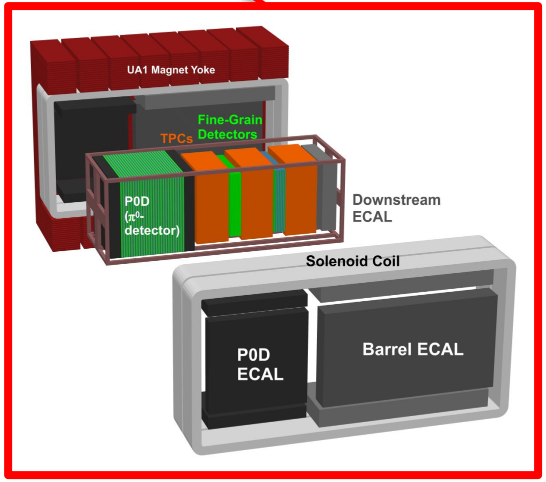
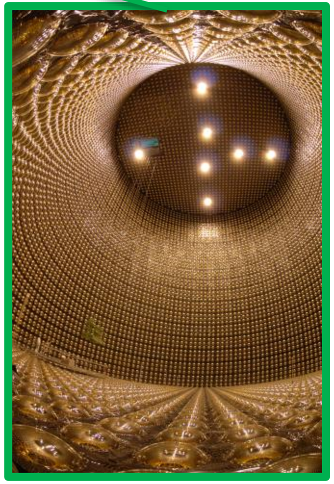
$$N_{obs} = \boxed{\Phi(E_\nu, \nu, \boldsymbol{\theta})} \times \sigma(E_\nu, \nu) \times \epsilon(\text{Detector}, E_\nu, \sigma) \times P_{\nu_x \to \nu_y}(\boldsymbol{\theta})$$







What does a near detector need to do?

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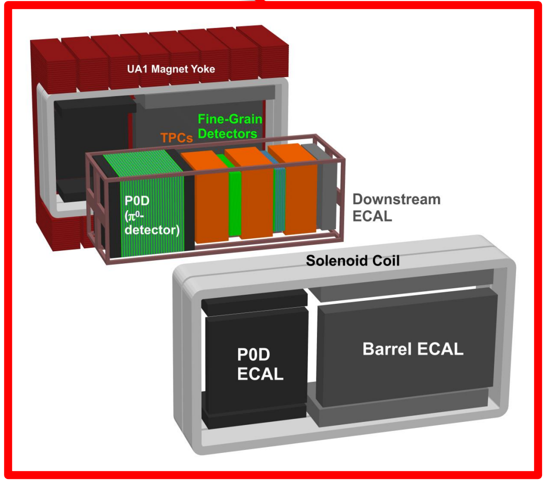
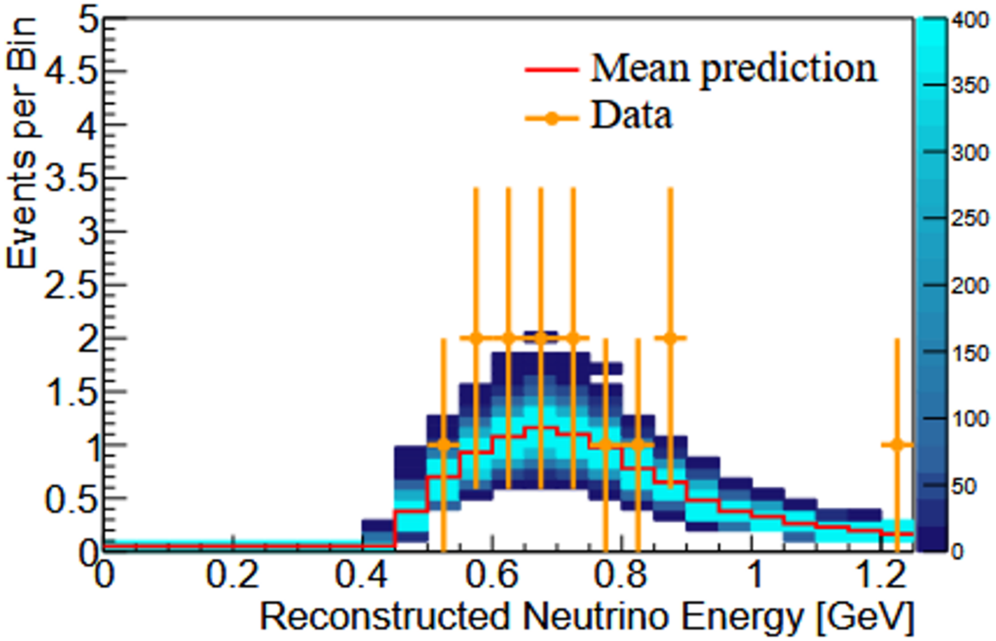
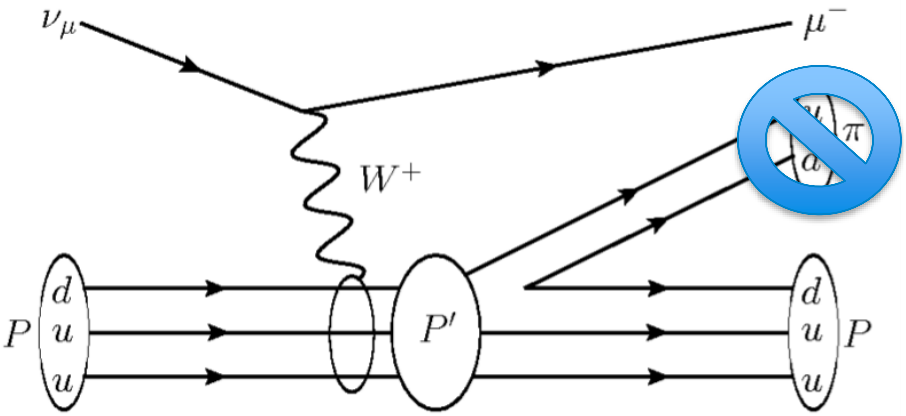
$$N_{obs} = \boxed{\Phi(E_\nu, \nu, \boldsymbol{\theta}) \times \sigma(E_\nu, \nu) \times \epsilon(\text{Detector}, E_\nu, \sigma)} \times P_{\nu_x \rightarrow \nu_y}(\boldsymbol{\theta})$$



- Consider how you measure neutrino energy, ability to understand neutrino interaction models, efficiency and phase space compared to the far detector

Phase space issues – example from T2K



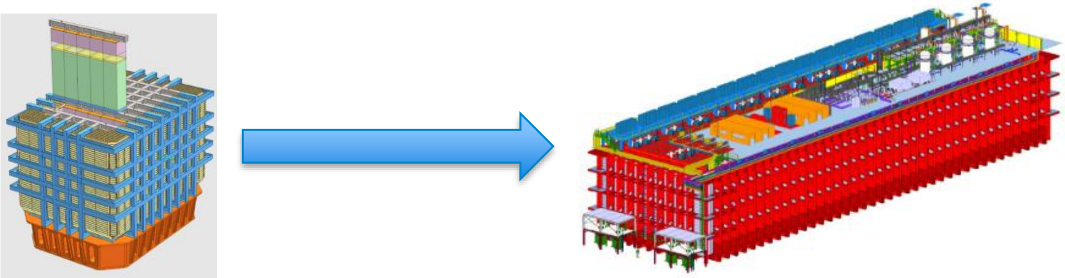


Single electron-like ring with a Michel electron

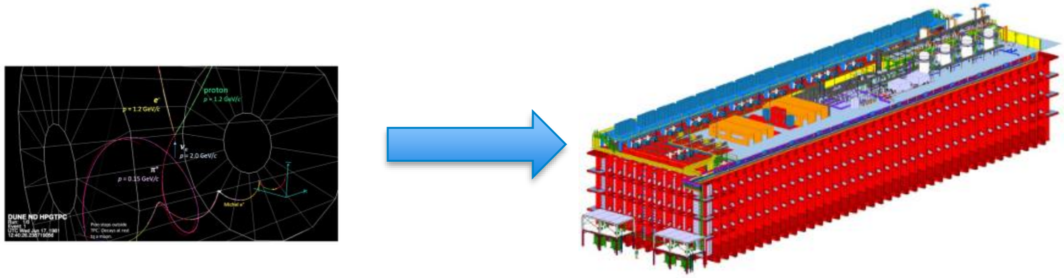
- SK uses Michel electron tag to locate pion – below Cherenkov threshold
- Rate hard to constrain at ND since CC-1Pi sample largely composed of pions above 400MeV/c (i.e. above Cherenkov threshold)
  - Large model uncertainty from pion-nucleus interactions

Different approaches

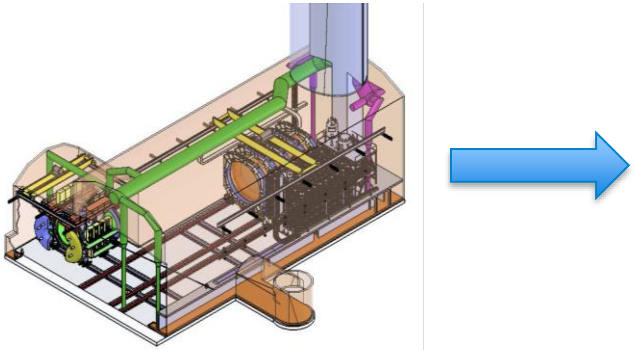
- Functionally identical detectors (NOvA)
  - Minimise efficiency phase space differences
  - Same energy reconstruction as FD (?)

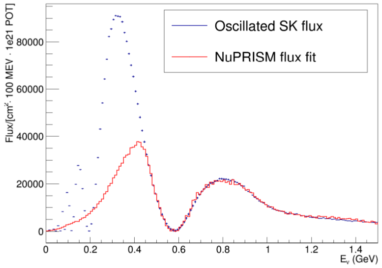


- “Better” detectors (T2K)
  - GArTPC has lower tracking threshold
  - Larger phase space, can correct to FD
  - More information to allow model discrimination



- “PRISM” – who even needs a model anyway?
  - Of course it still needs a model…





My view on near detectors

- Need to measure shape of neutrino beam, direction and intensity
  - Identical detector(s) that take data from the centre of the beam to periphery
  - PRISM works for this

- Measurements will be limited by systematics, not statistics
  - Larger FD, higher beam power, longer exposure will have limited returns
    - How much do you gain by running for an extra year; cost of beam vs cost of near detector?
  - ND does not need more events, but better events

- No single approach can provide all the answers – do all of them!
  - GArTPC to differentiate between interaction models
  - LArTPC to perform near-far extrapolation
  - PRISM to ensure results are without bias

My view on future experiments

- DUNE and Hyper-K may be last accelerator-based long-baseline neutrino experiments
  - Imperative that we maximise physics from these experiments
  - Joint analysis required

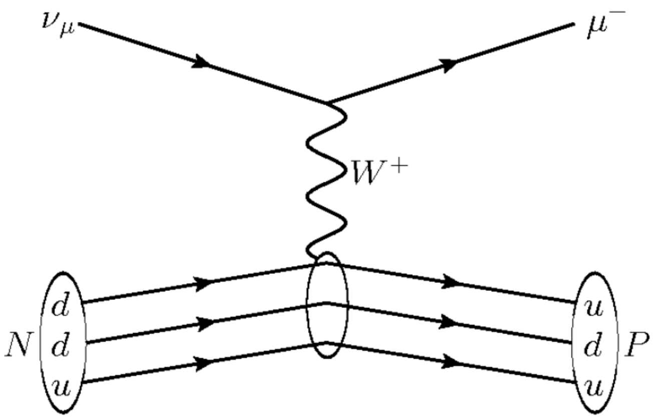
- More open discussion between collaborations, in particular discussion of ongoing T2K+NOvA joint analysis, essential

- Should consider building GAr/LAr detector at J-PARC and carbon/water detector at Fermilab
  - PRISM to test energy dependence, can have ~identical detector spanning neutrino energies from ~400 MeV up to ~few GeV
  - Better still, νSTORM with argon and water detectors to really measure interactions to <1% level

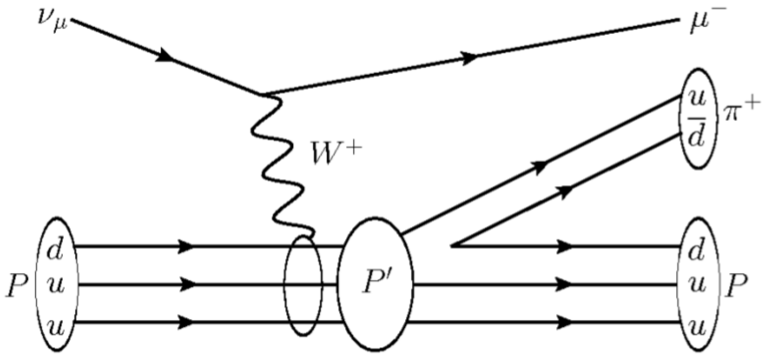
Backup Slides

Neutrino interactions

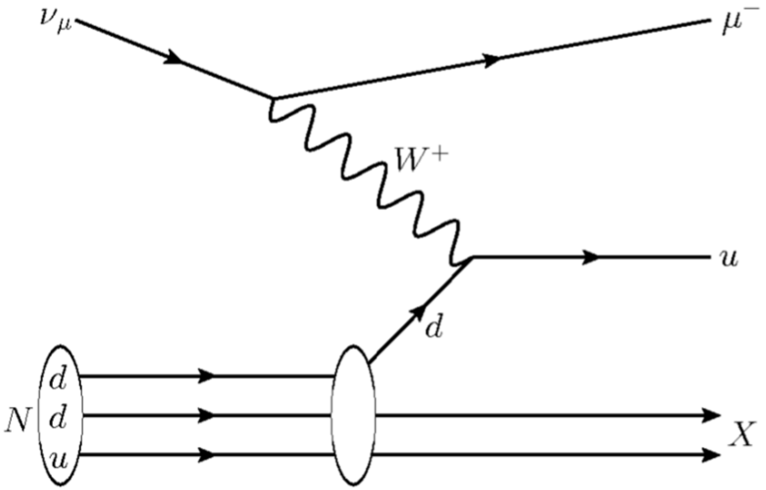
- Three principal types of neutrino interaction
- Occur as both charged current (CC) and neutral current processes



Quasi-elastic (CCQE)

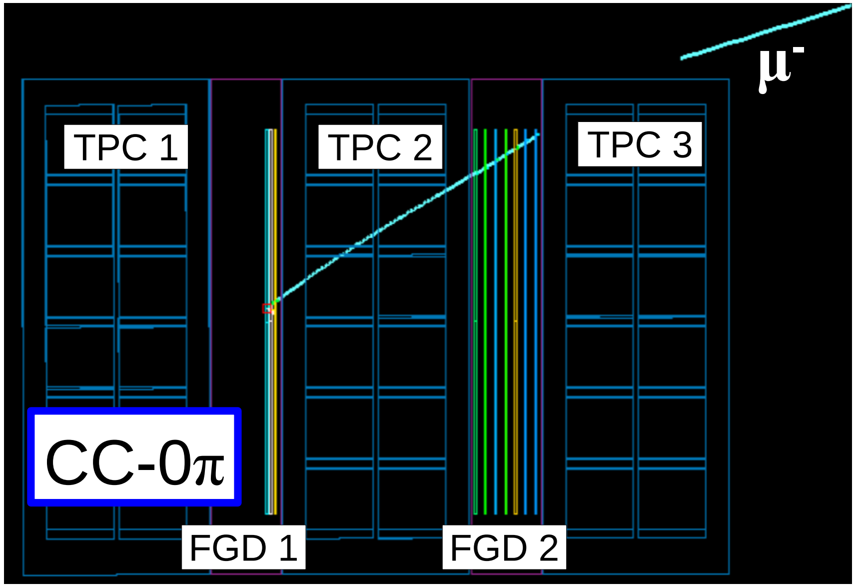


Single pion production

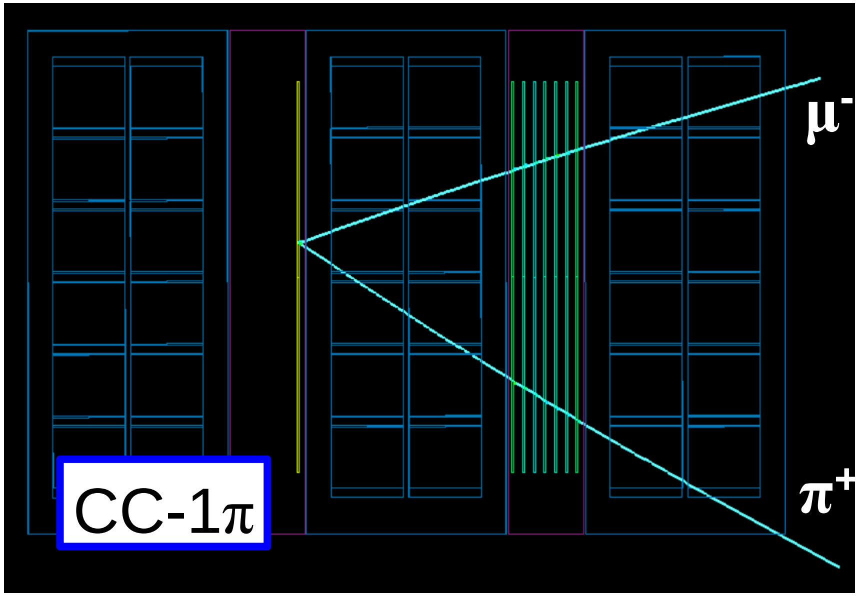


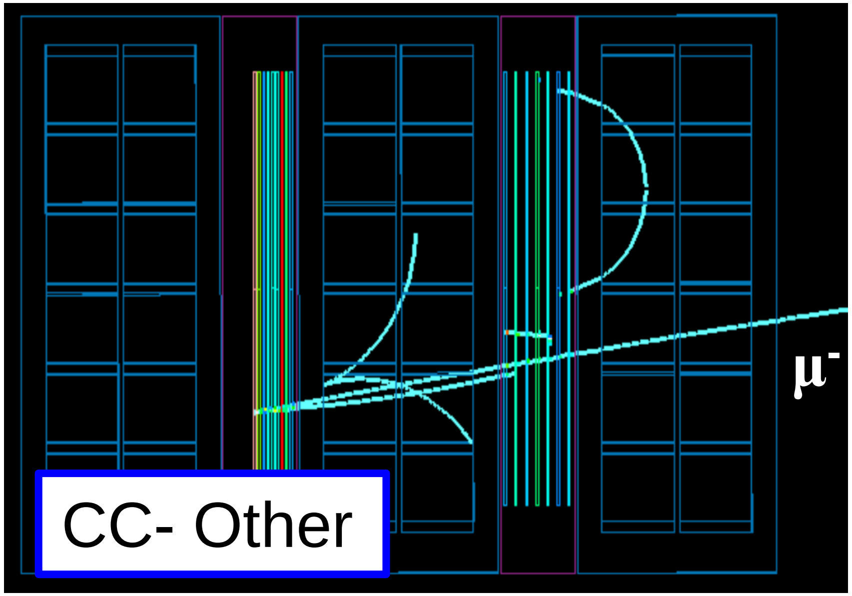
Deep inelastic scattering / Multi-pion production

ND280 data

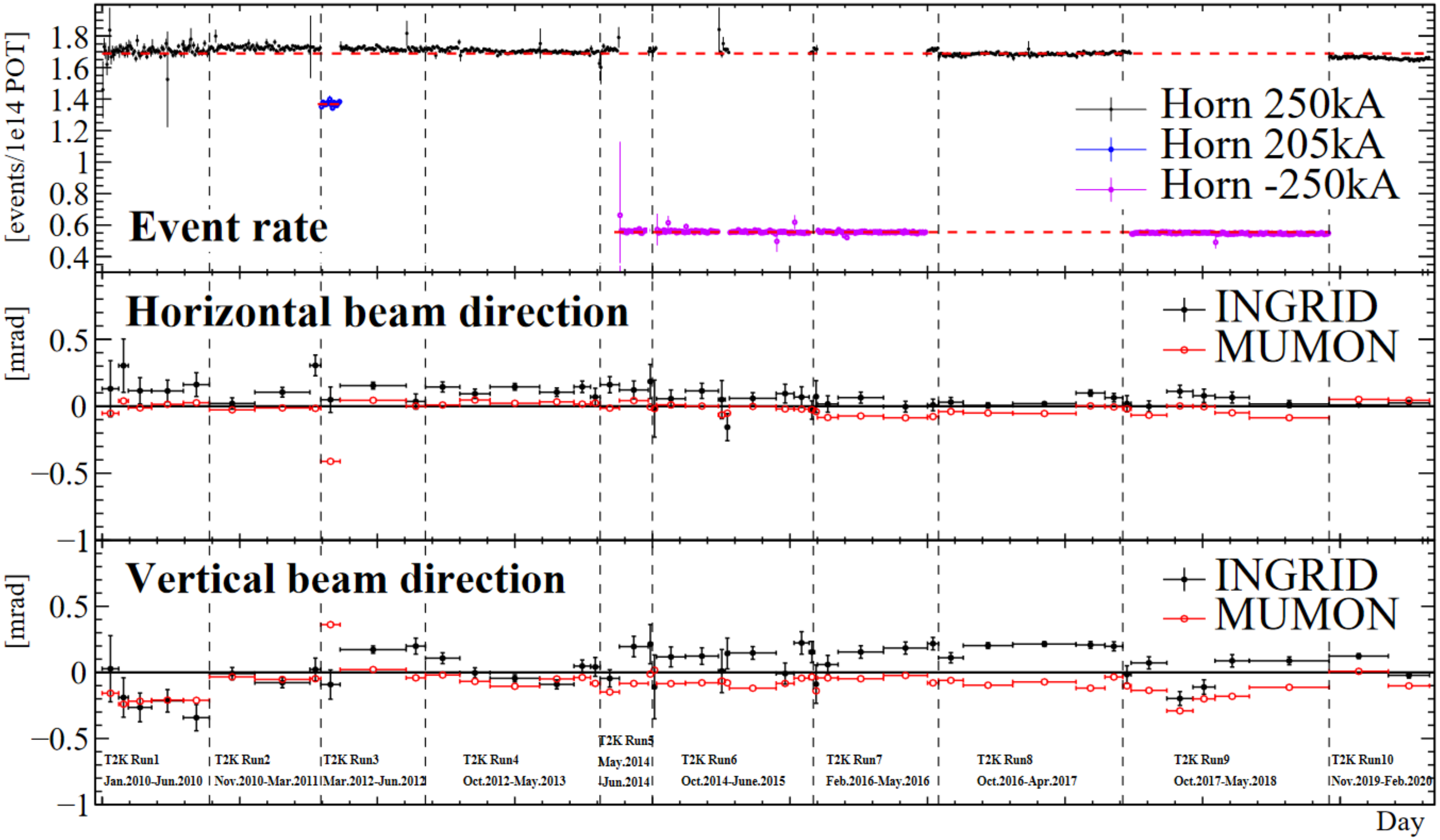


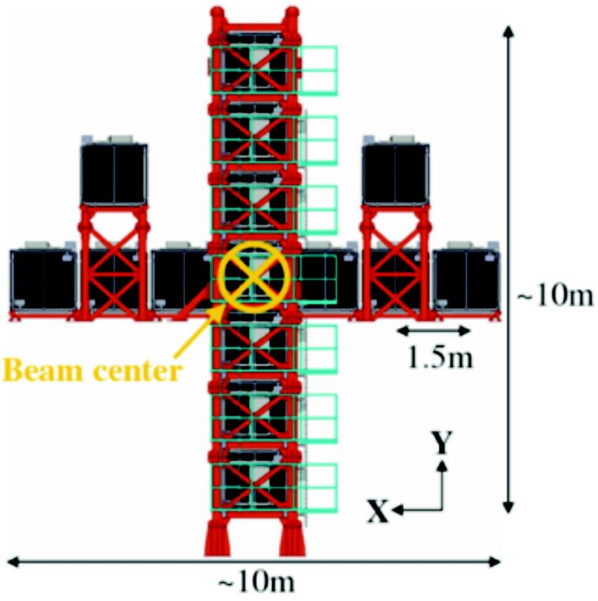
- Three principal types of neutrino interaction
- Occur as both charged current (CC) and neutral current processes





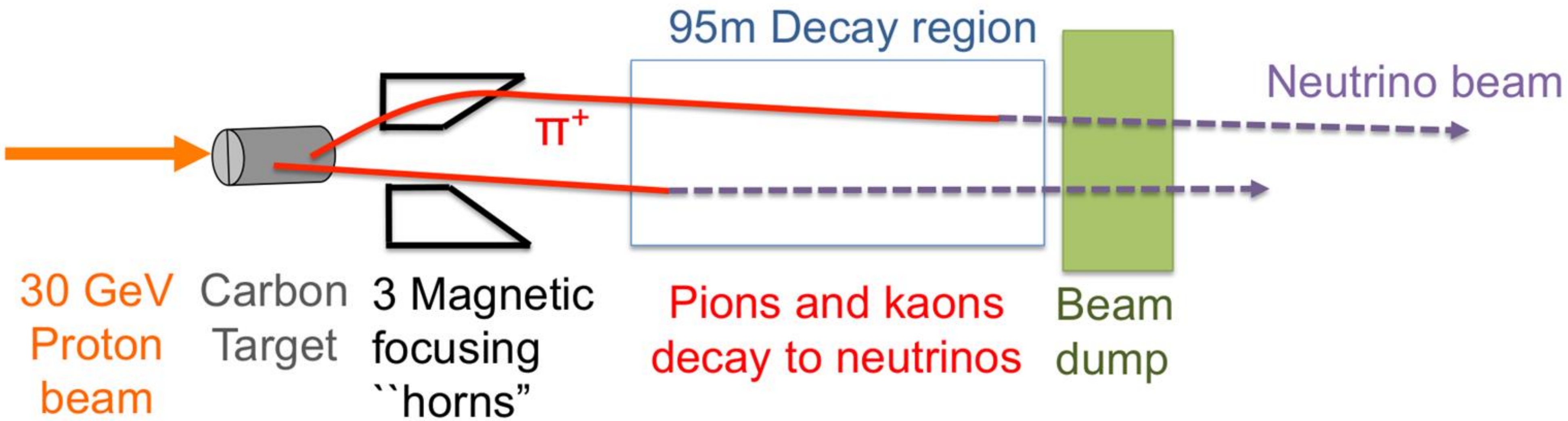
Beam stability



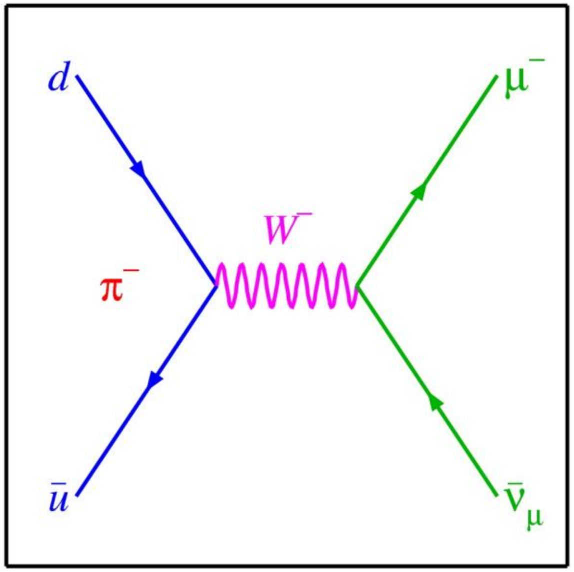


- INGRID and muon monitors measure beam centre position
- Very stable neutrino beam over full run

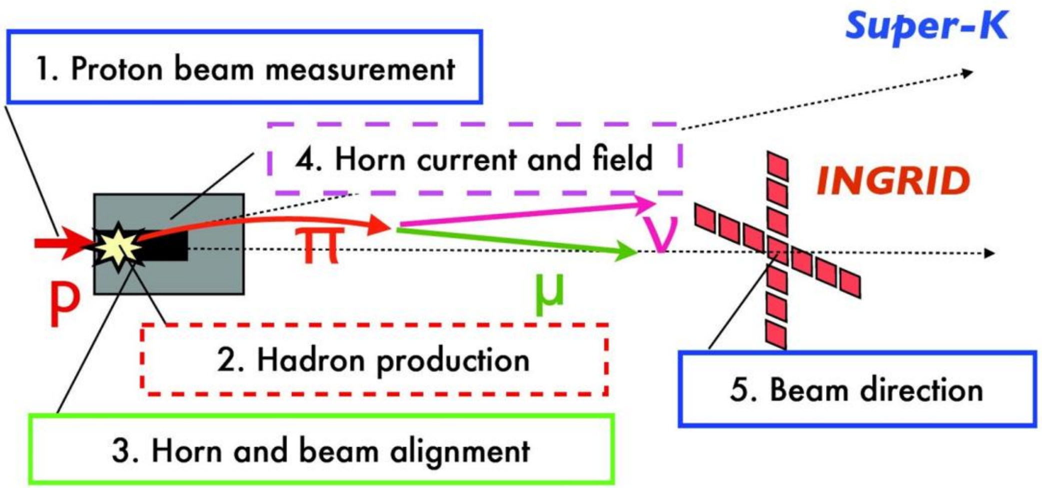
Neutrino beams

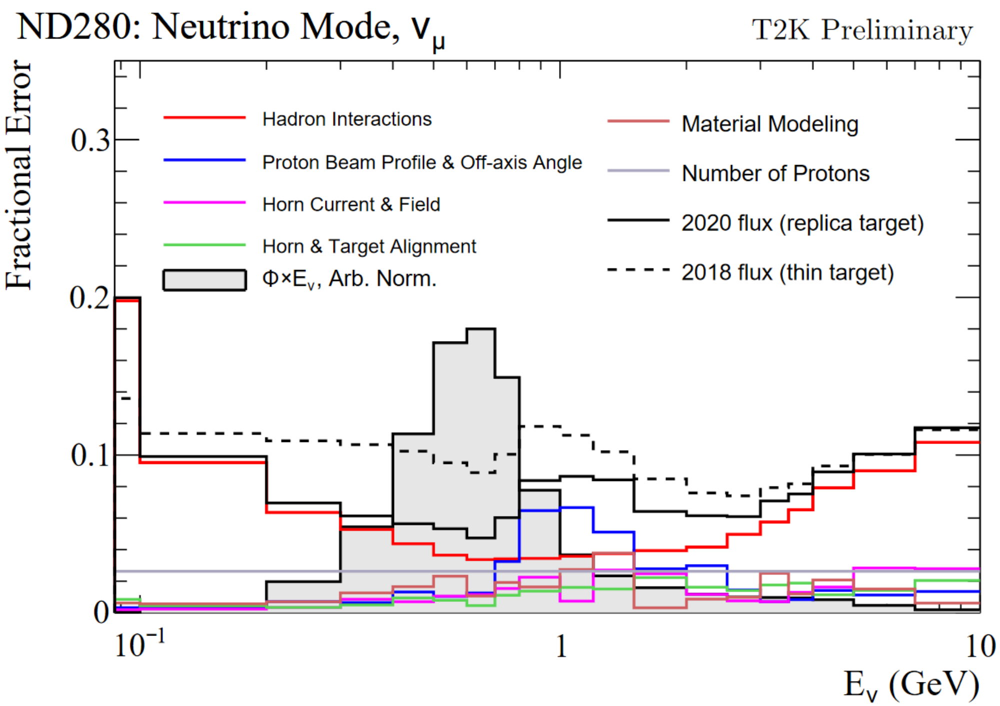


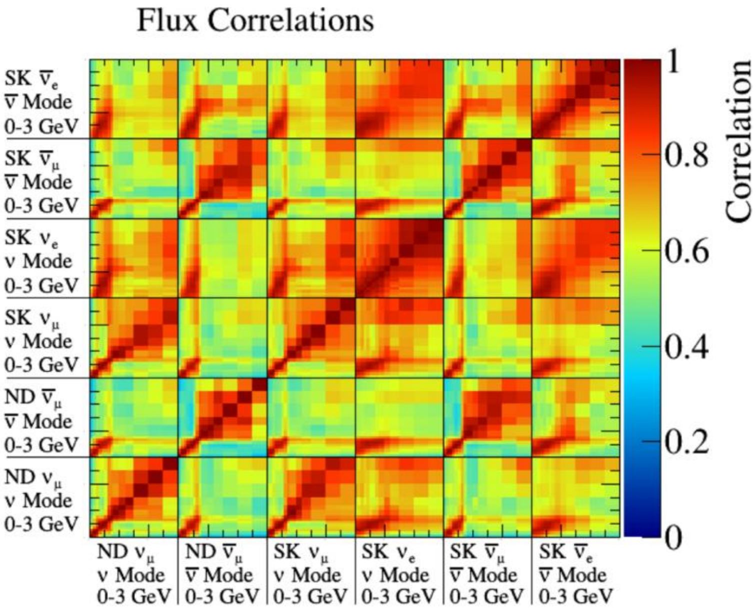
- Proton beam collides with fixed target to produce charged mesons
- Focus positive or negative mesons to produce neutrino-dominated or antineutrino-dominated beam
- Wait for pions to decay into neutrinos



T2K flux model



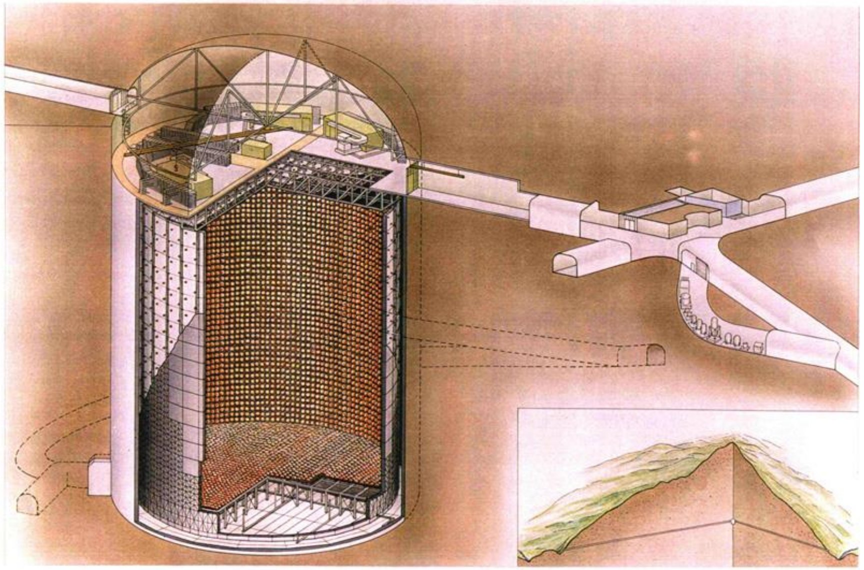




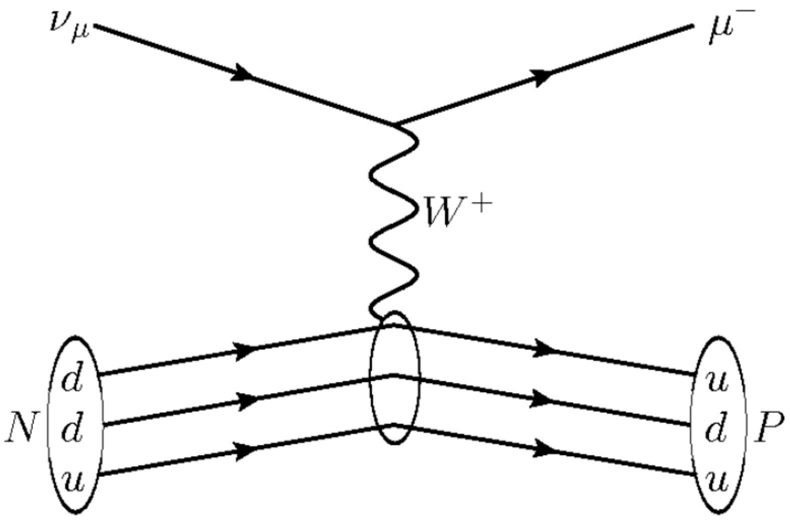
- Parametrised in neutrino energy and flavour
- Parameter uncertainties calculated by varying underlying systematics
- Performed simultaneously for near and far detector
- Correlates near and far flux parameters

Super-Kamiokande detector

- Signal in far detector:
- Measure rate of muon-like and electron-like events
- CCQE interactions are 'golden' channel



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO (c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo NIKKEN SEKKEI



(a) CC QES interaction

- Assume nucleon at rest – 2-body process
- Can calculate neutrino energy from observed muon kinematics

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

SK event selection – 0π samples

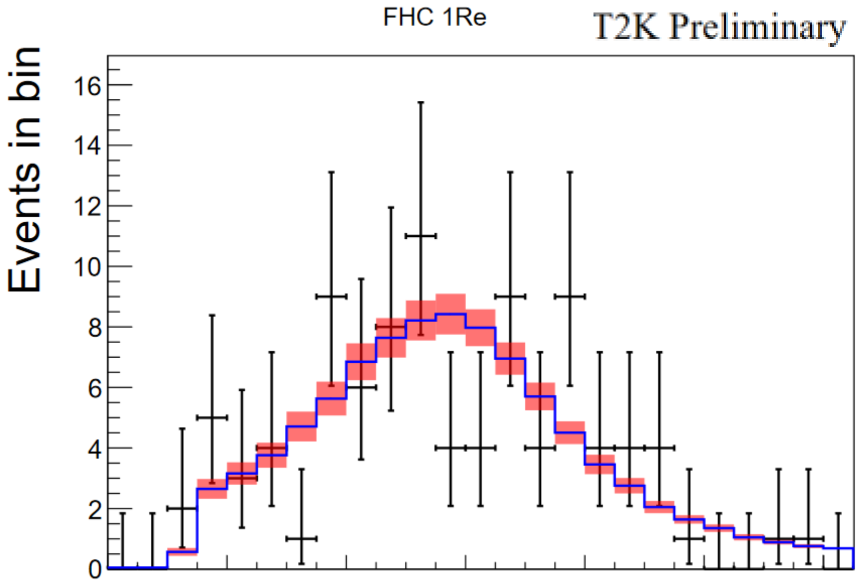
Look for fully contained, single ring events inside SK fiducial volume, then:

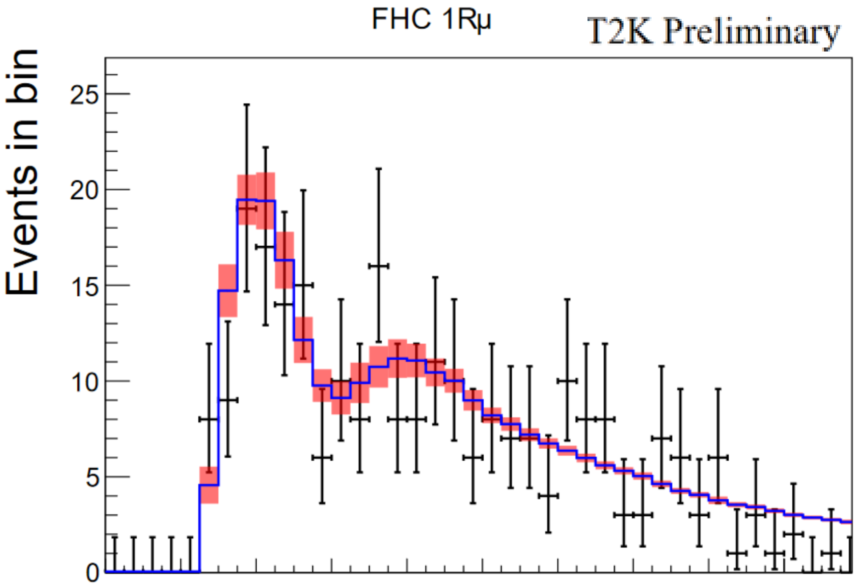
If electron-like ring:

- Visible energy > 100 MeV
- Reconstructed energy < 1250 MeV
- Not identified as π^0
- No decay electrons

If muon-like ring:

- Reconstructed momentum > 200 MeV/c
- At most 1 decay electron



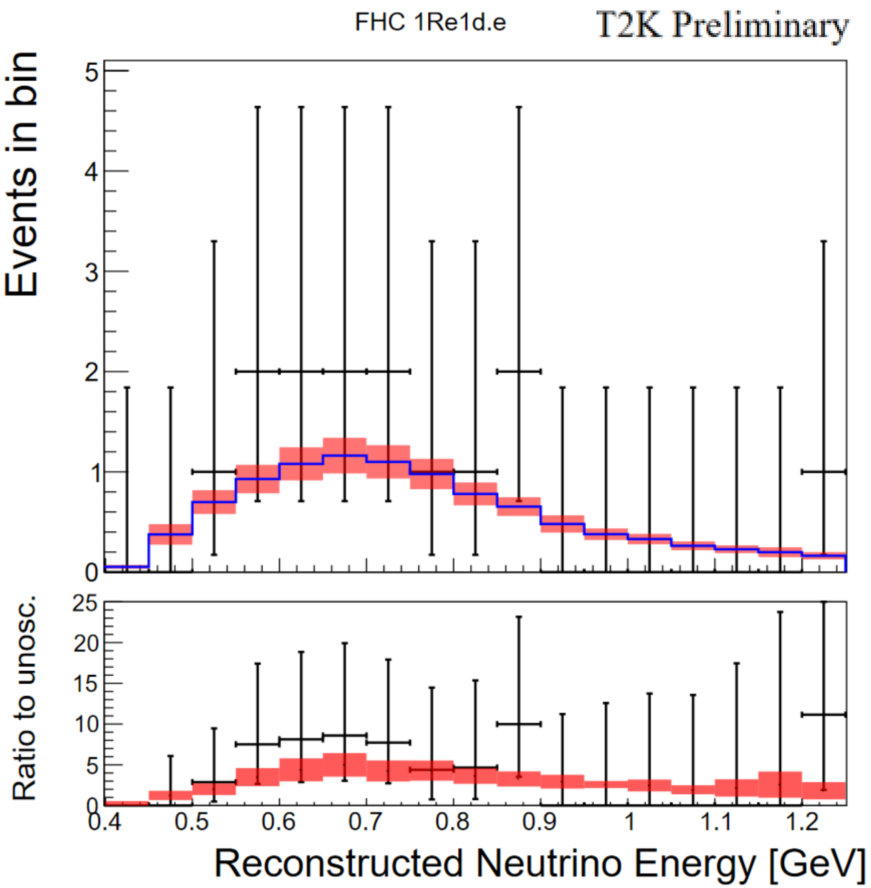


SK event selection – e-like single pion sample

Look for fully contained, single ring events inside SK fiducial volume, then:

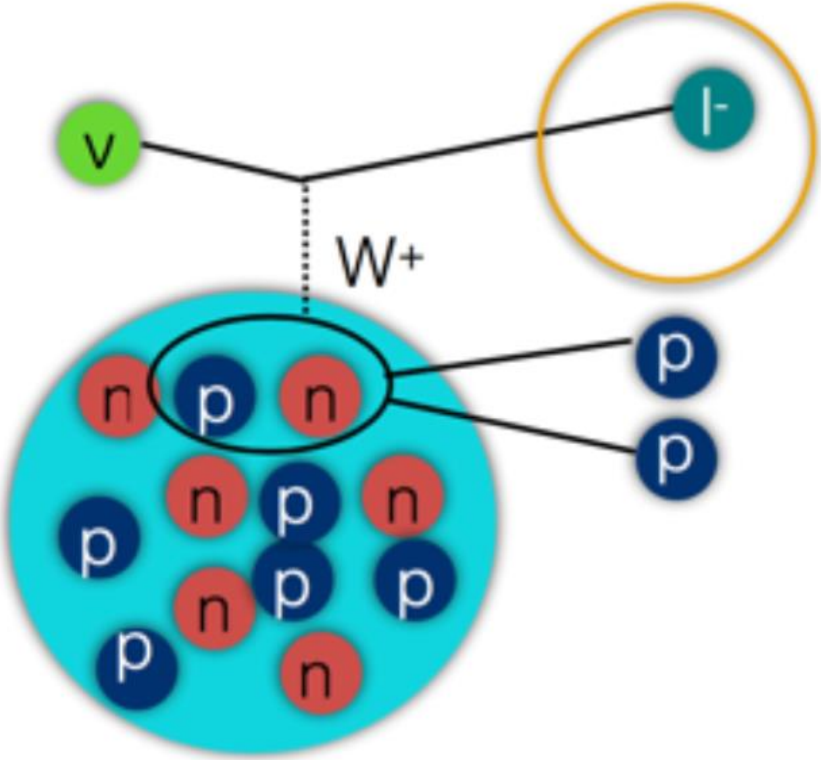
If electron-like ring:

- Visible energy > 100 MeV
- Reconstructed energy < 1250 MeV
- Not identified as π^0
- **One** decay electrons

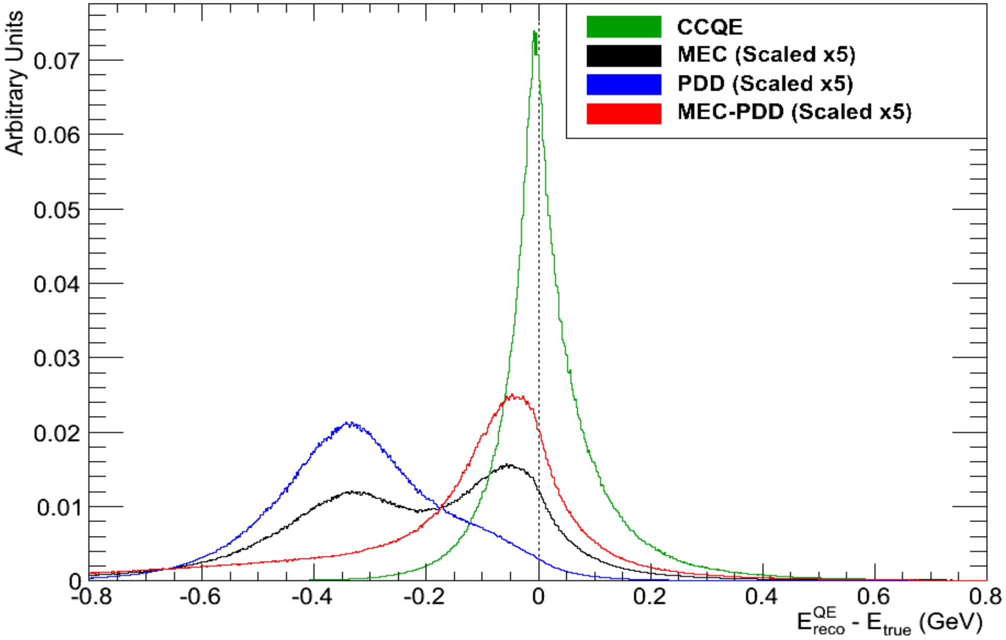


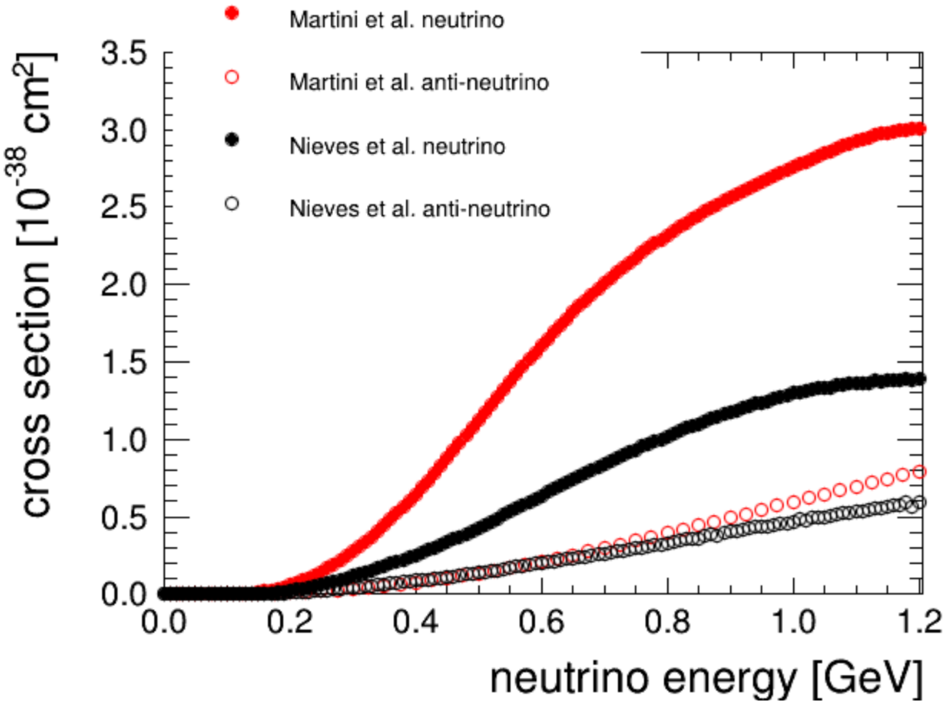
Example: 2p-2h events

- Lepton kinematics give energy
- Extra protons below detector threshold – missed energy
- If we get the model wrong
  - Biased energy reconstruction
  - Incorrect relationship between reconstructed and true neutrino energy



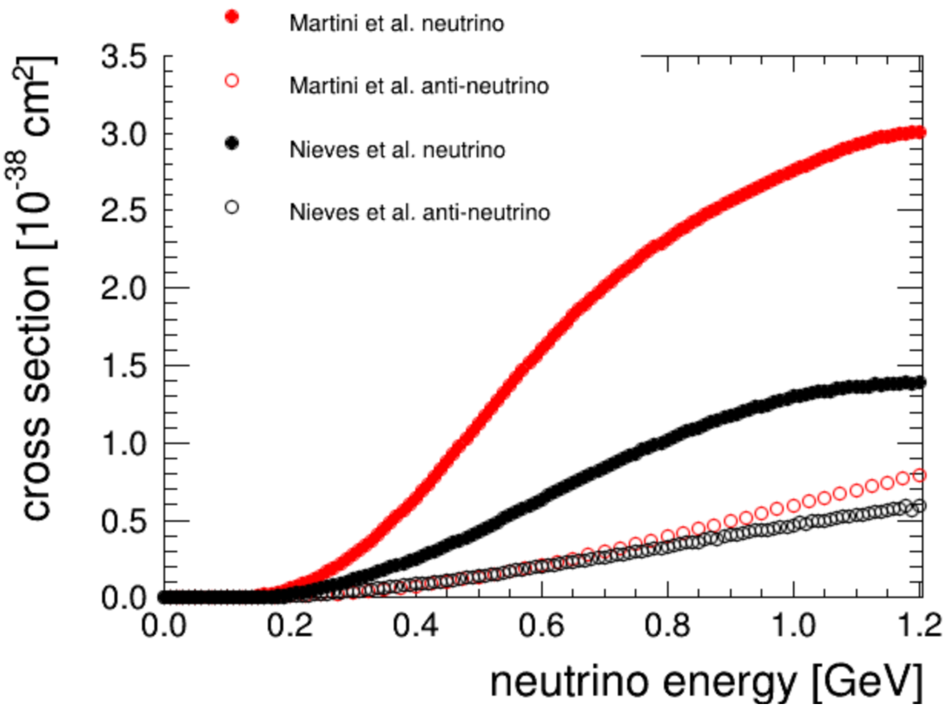
2p-2h event reconstruction

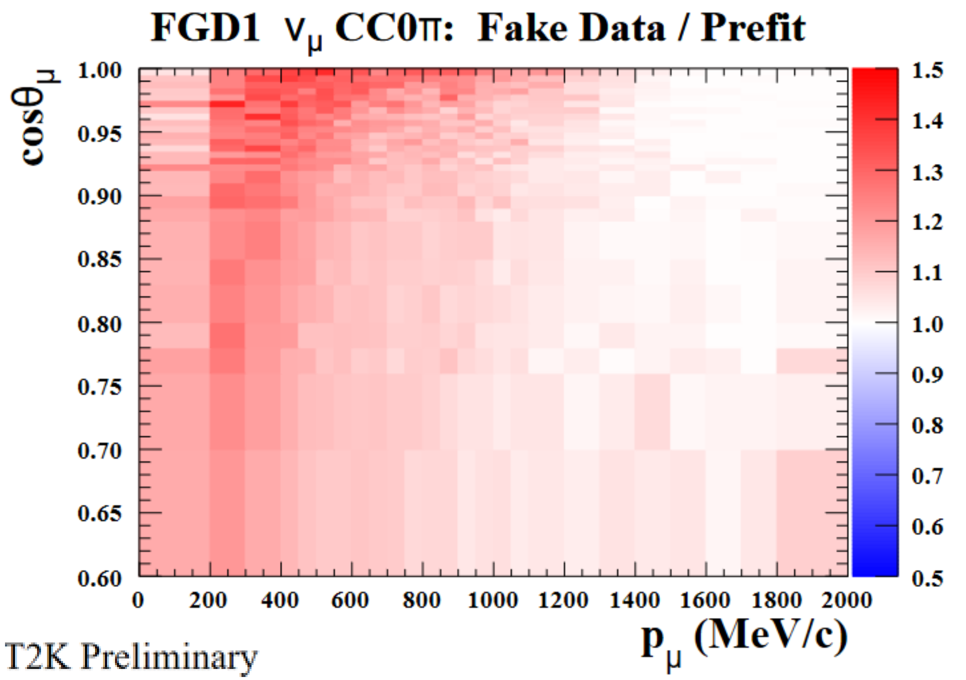




- Biased energy affects oscillation measurements
- Multiple possible models – Martini and Nieves are two examples
  - Different predicted rates for neutrinos and anti-neutrinos
  - ‘CP-violating’ uncertainty

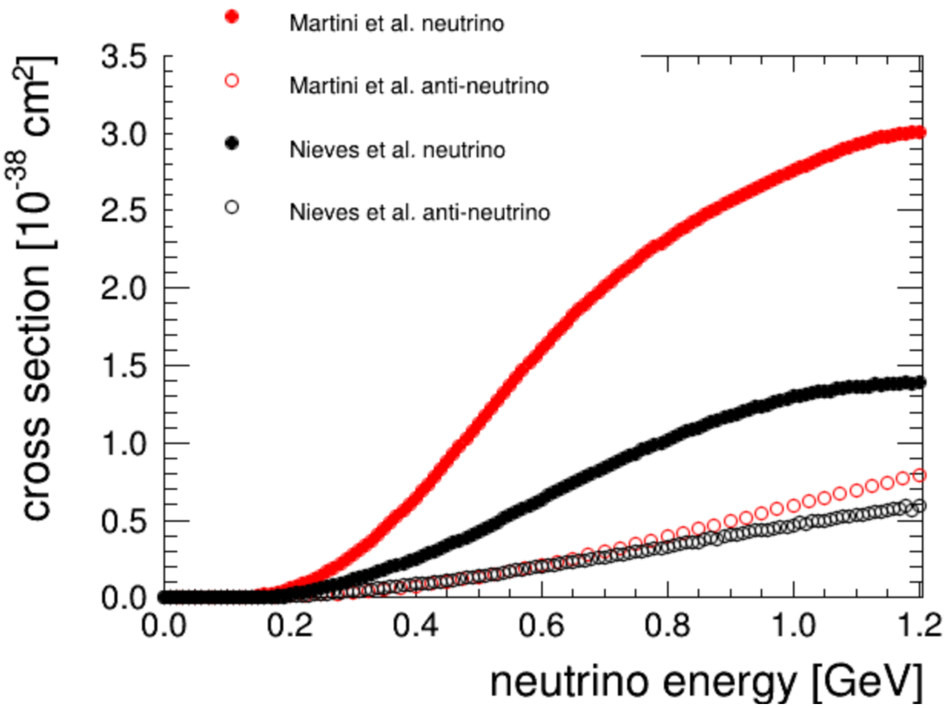
The Martini 2p2h simulated data study

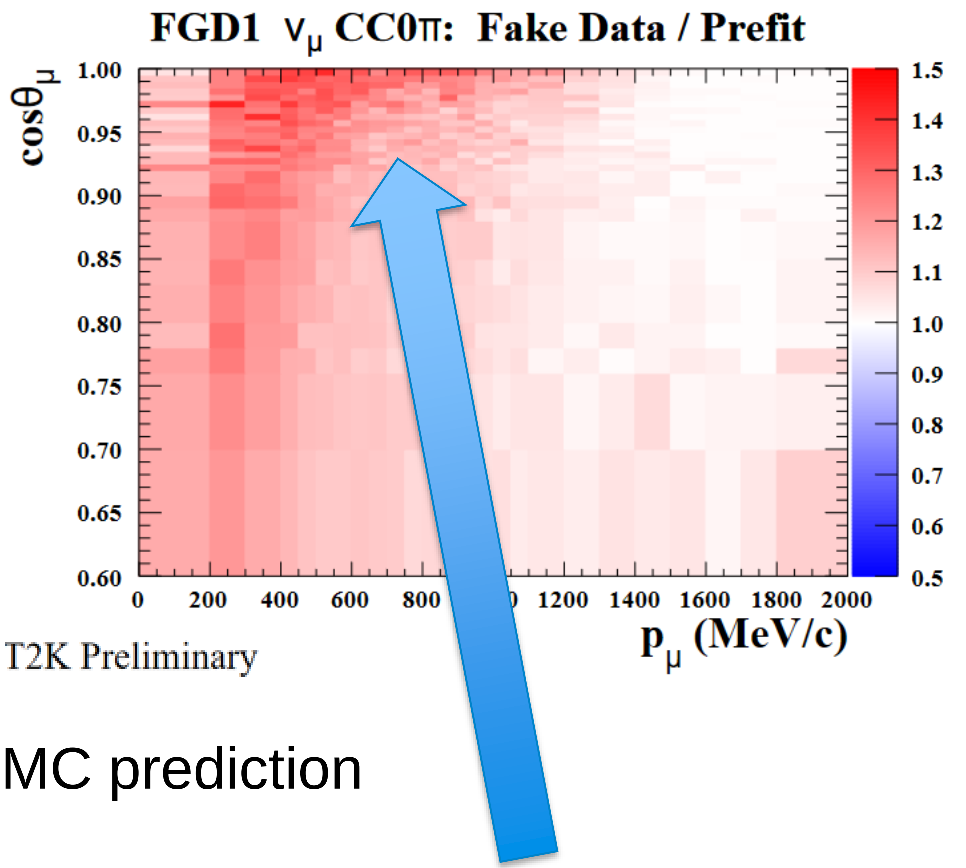




- Model applied to ND280 nominal MC prediction
- FGD1 CC0π sample shown

The Martini 2p2h simulated data study

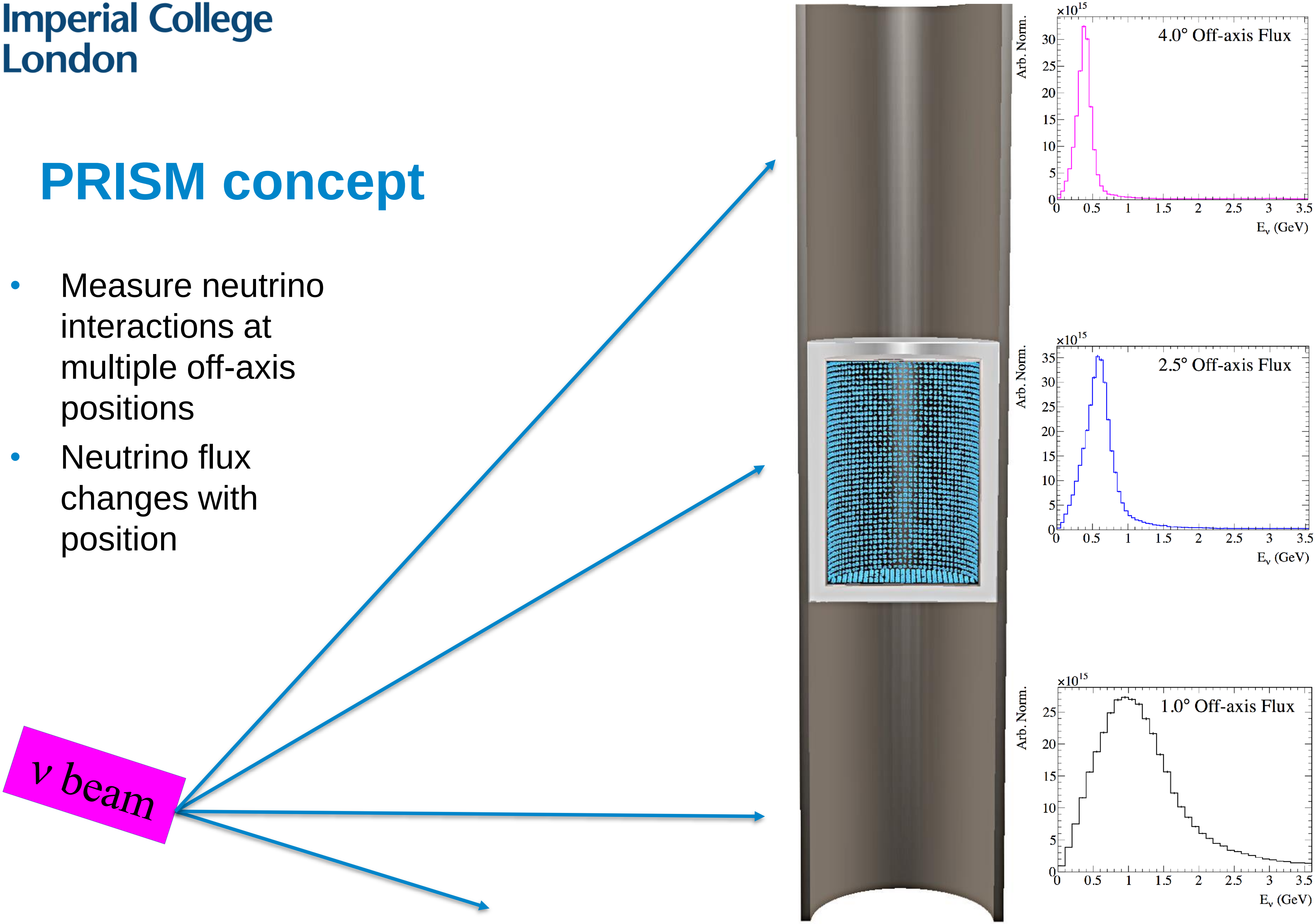




- Model applied to ND280 nominal MC prediction
- FGD1 CC0π sample shown
- Increase in normalization with larger increase at larger neutrino energies

PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position



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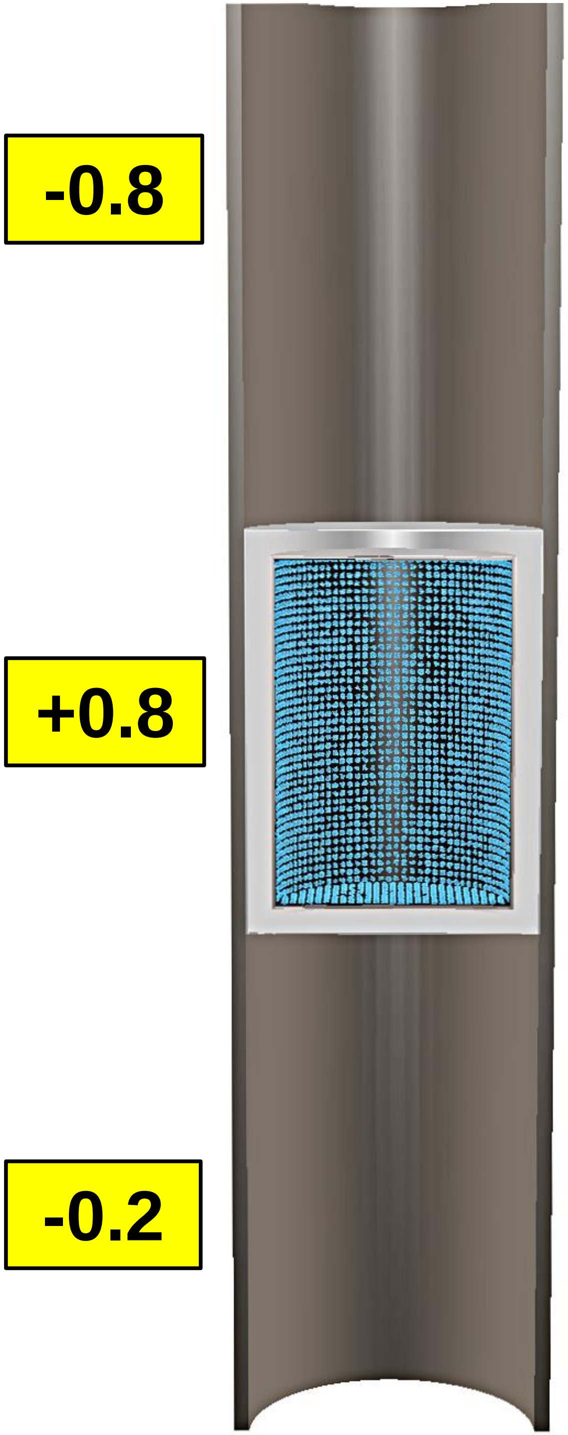
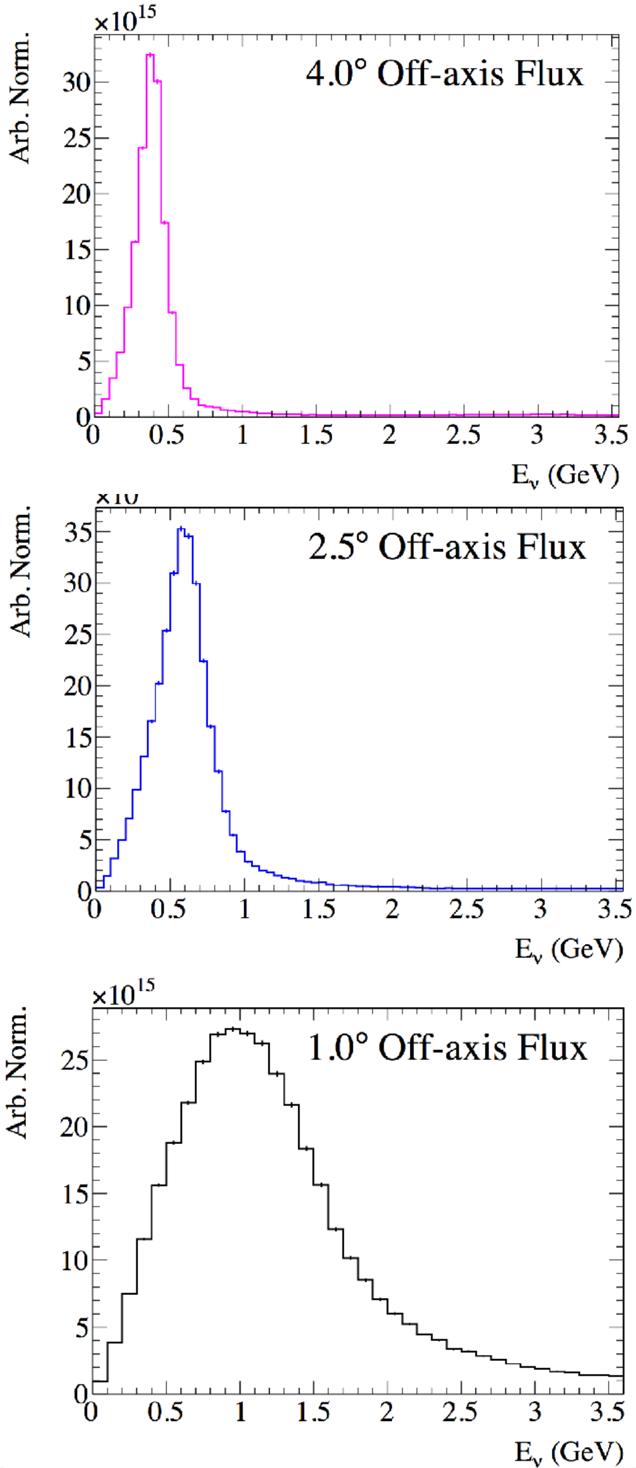
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’





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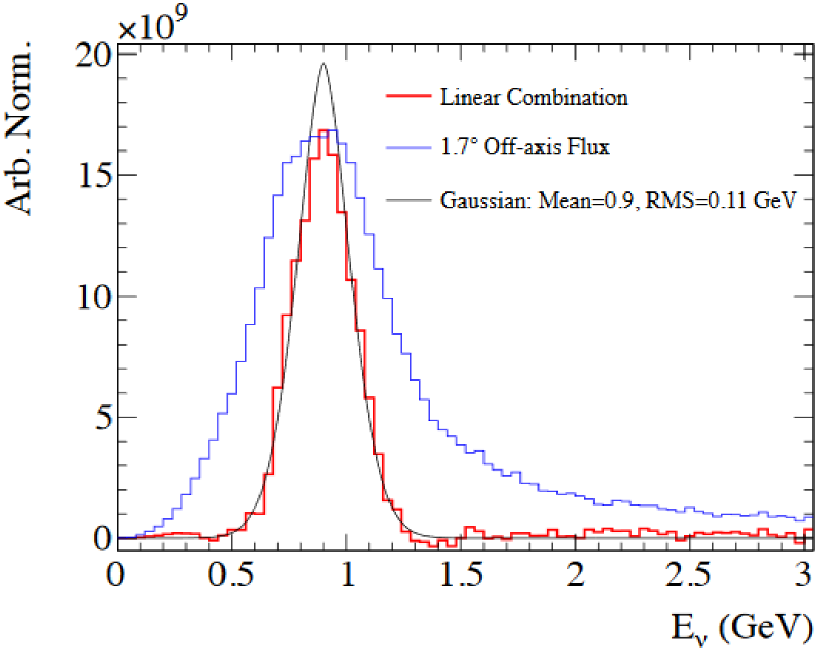
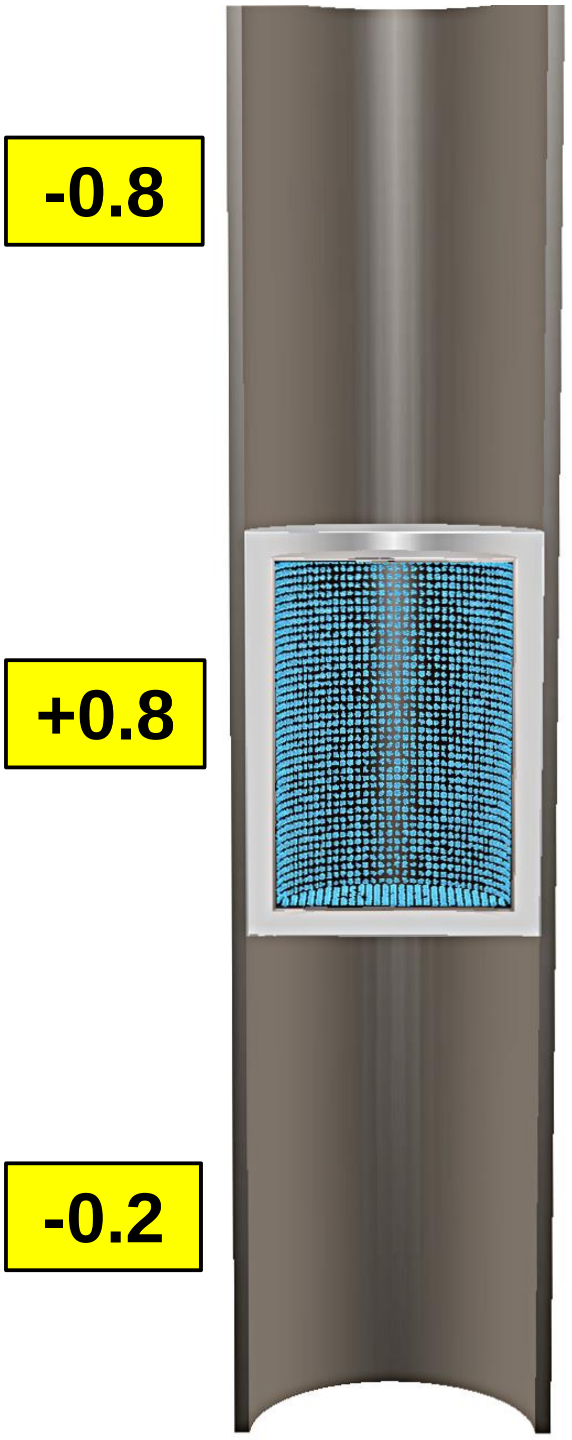
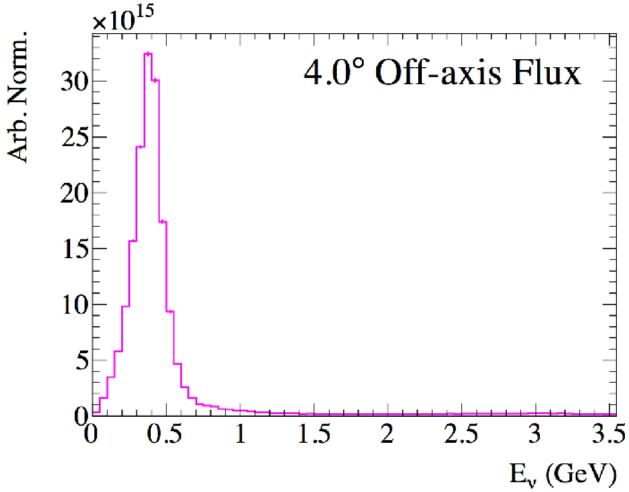
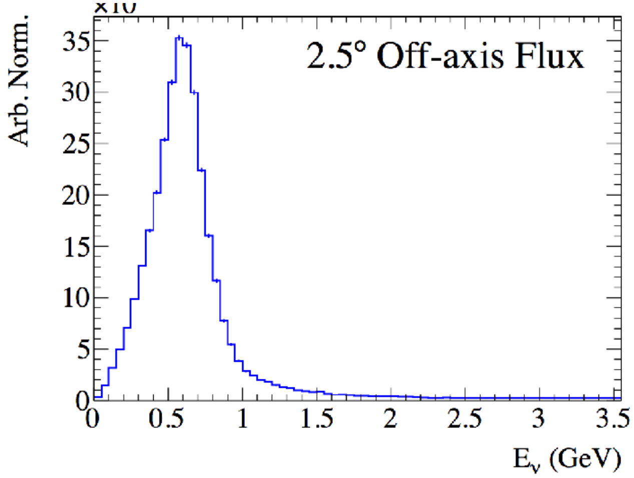
PRISM benefits - 2

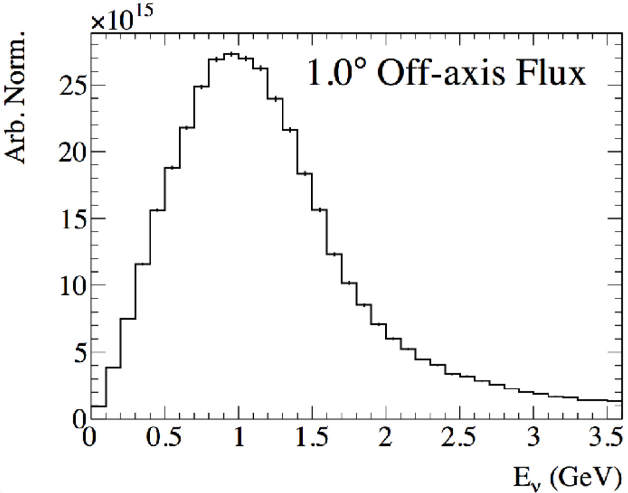
- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution





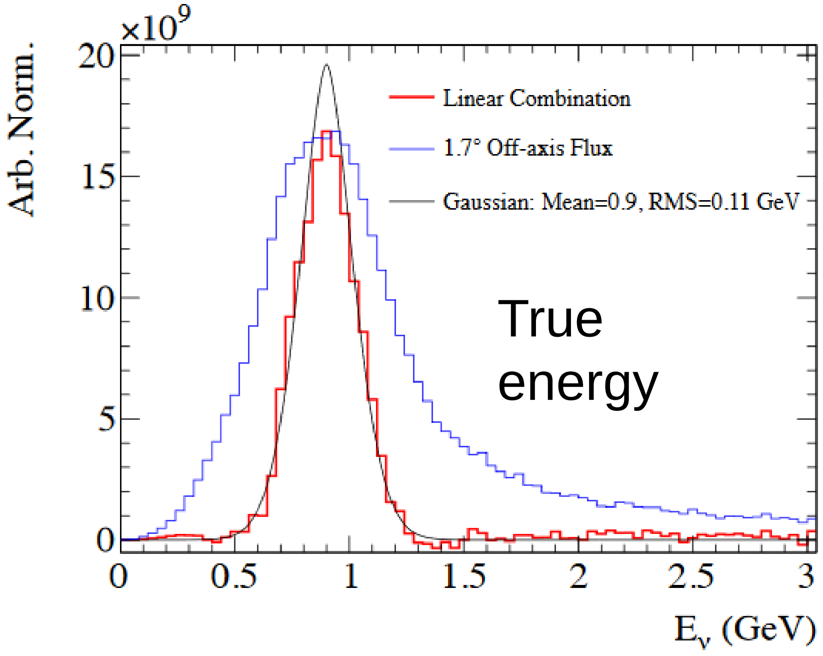






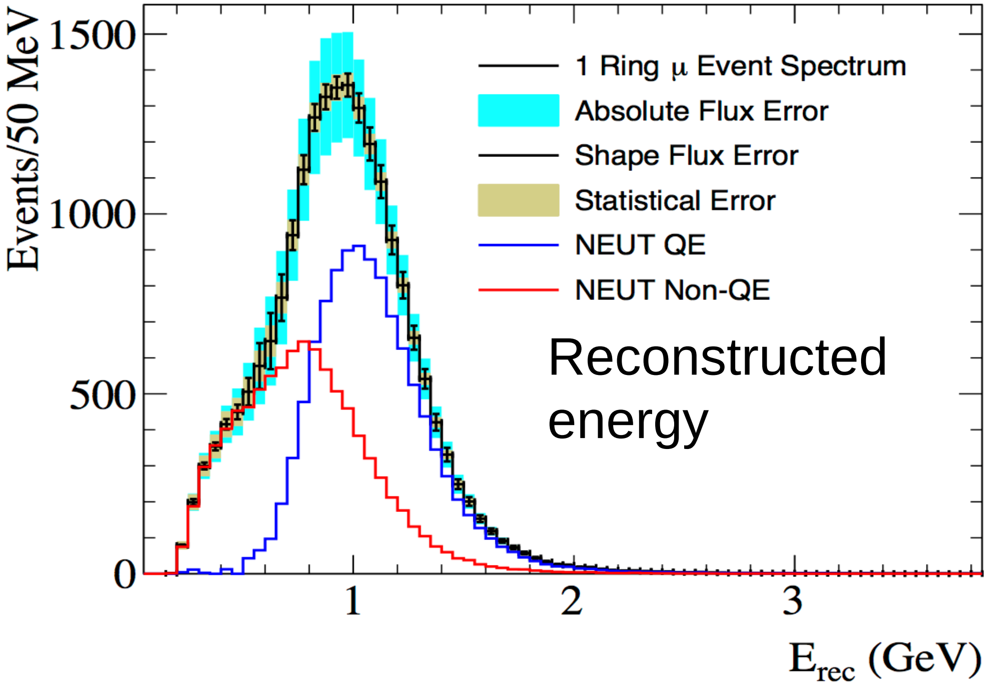
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution



- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range

Linear Combination, 1.2 GeV Mean



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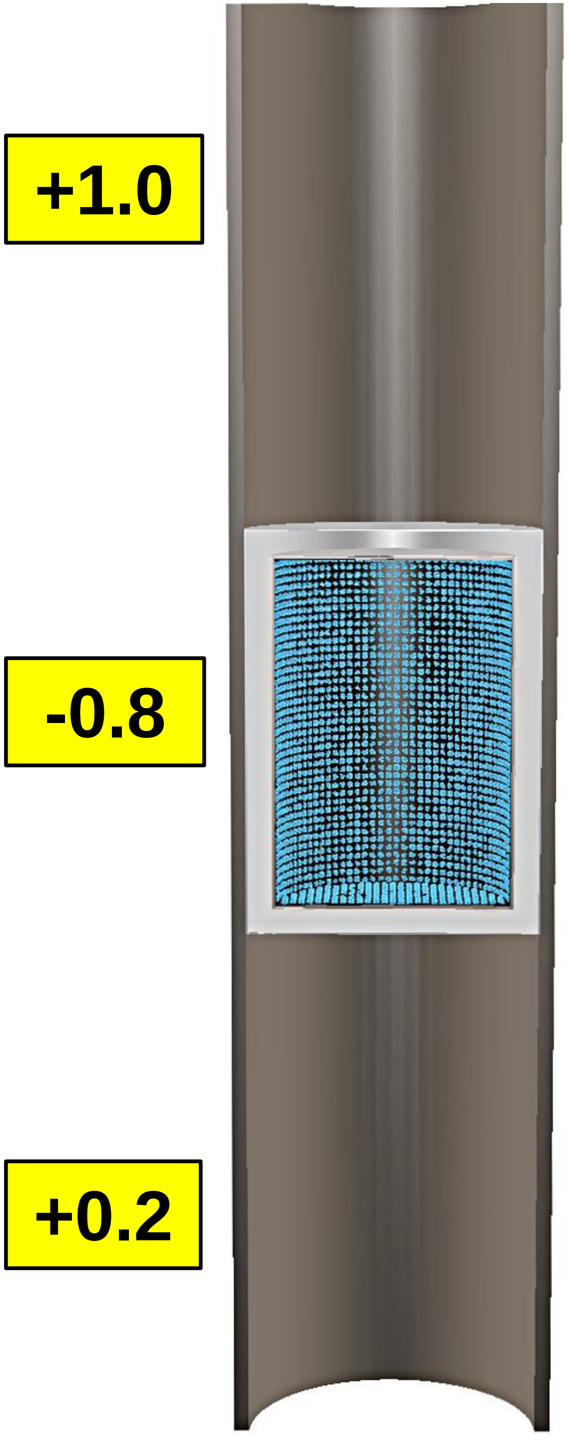
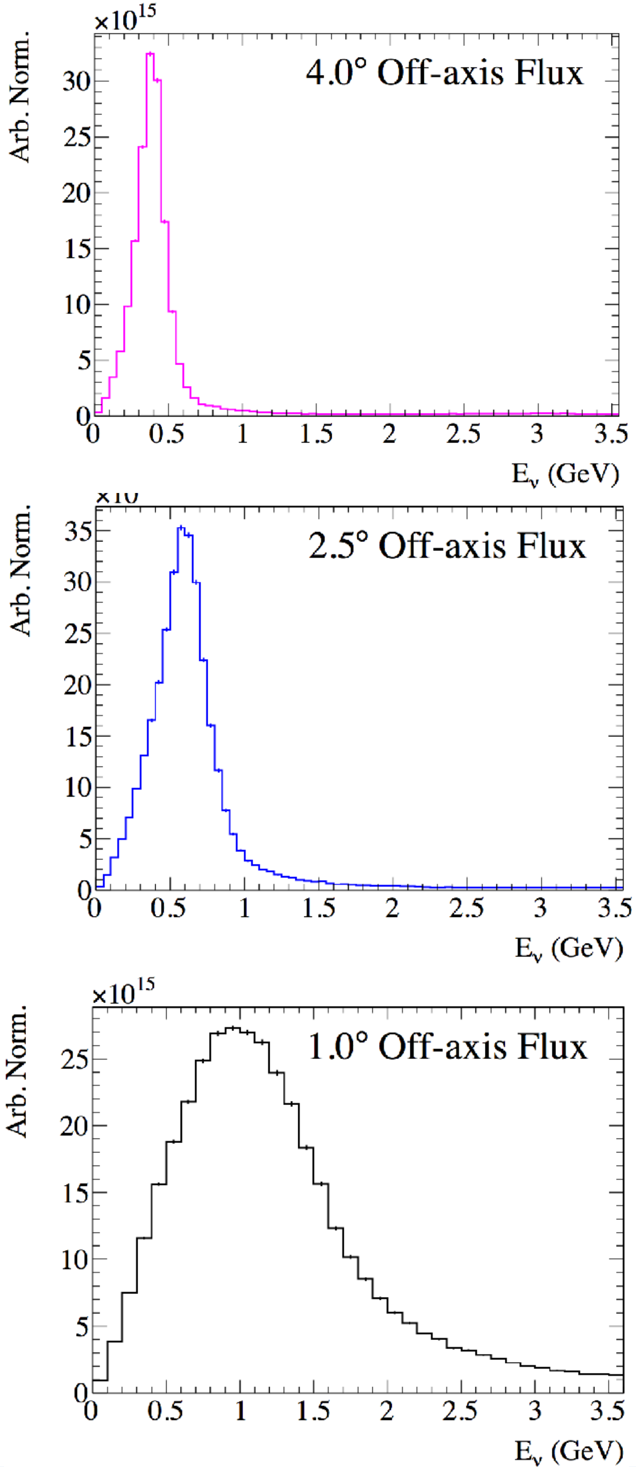
PRISM benefits - 3

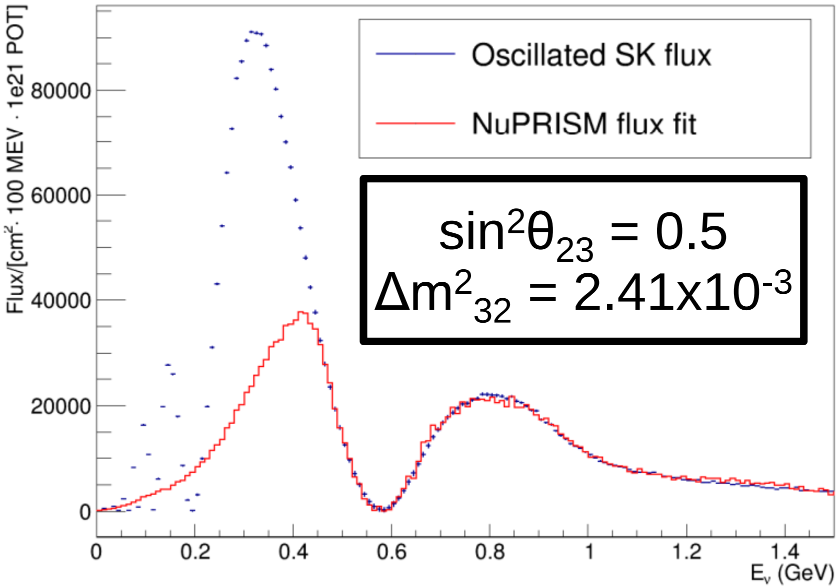
- Can have different linear combination





PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data

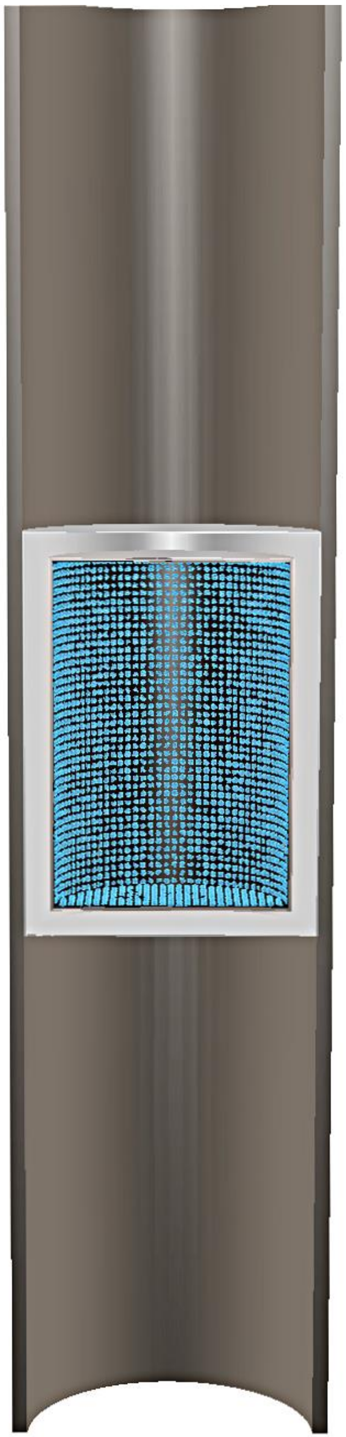


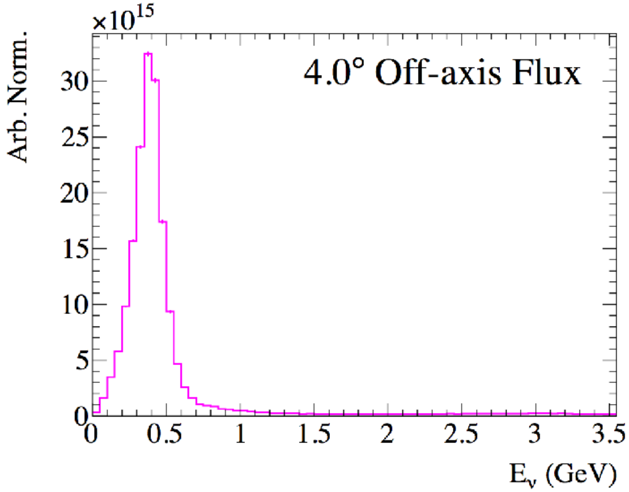
$$\sin^2\theta_{23} = 0.5$$
$$\Delta m^2_{32} = 2.41\text{x}10^{-3}$$

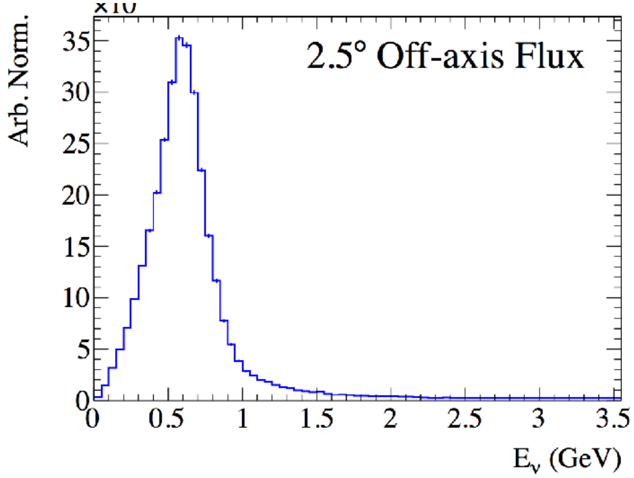
+1.0

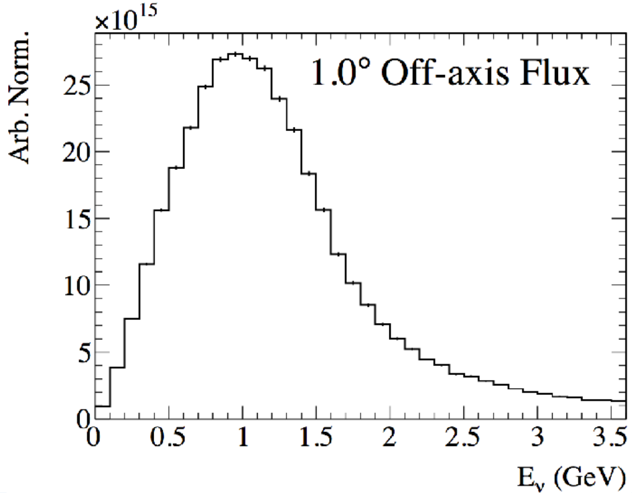
-0.8

+0.2



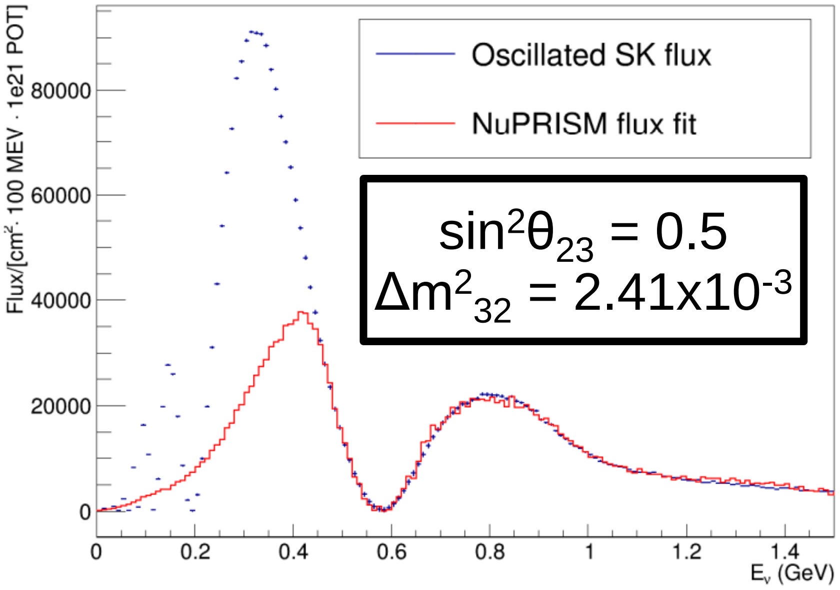




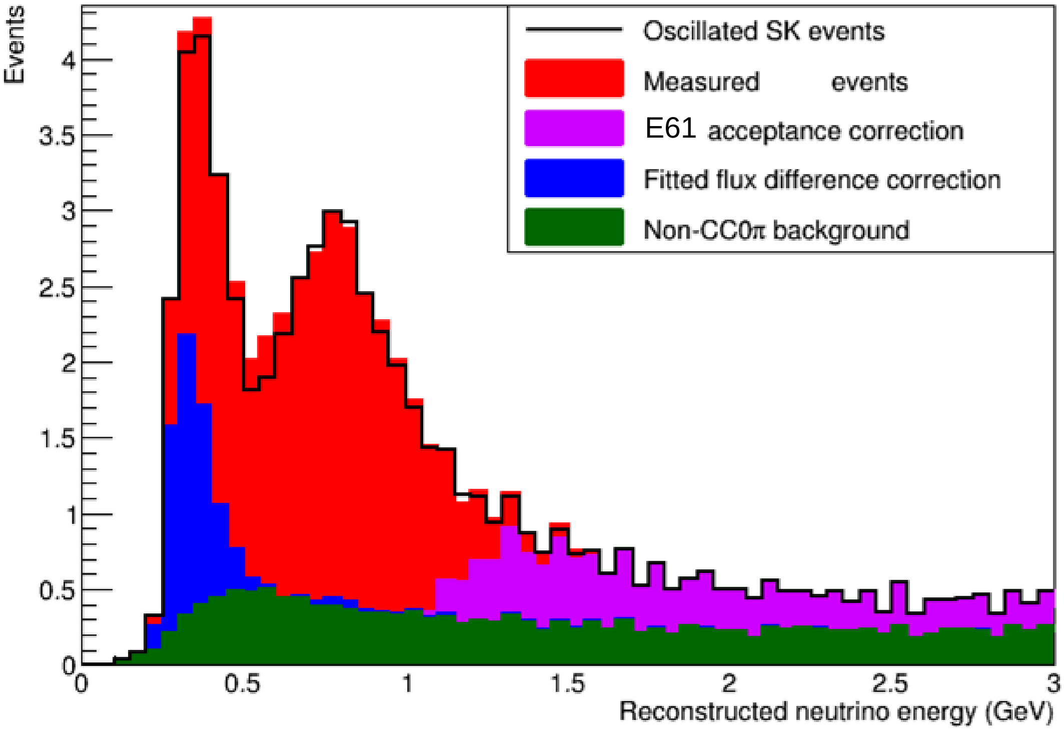


PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data

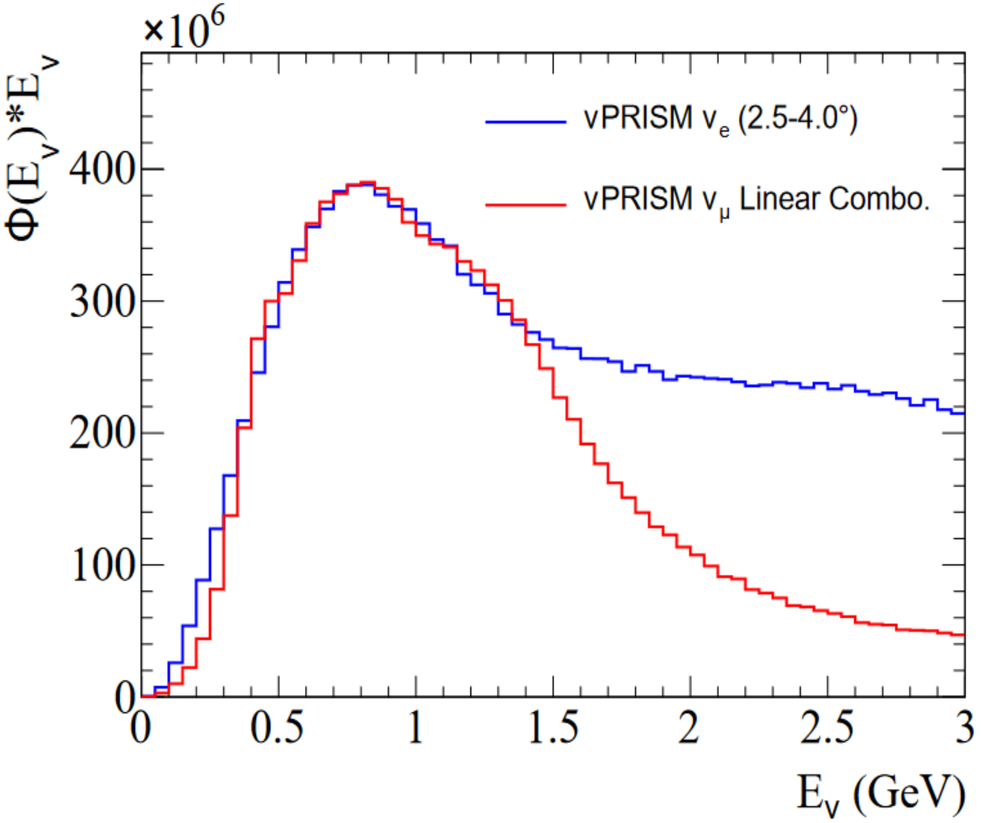


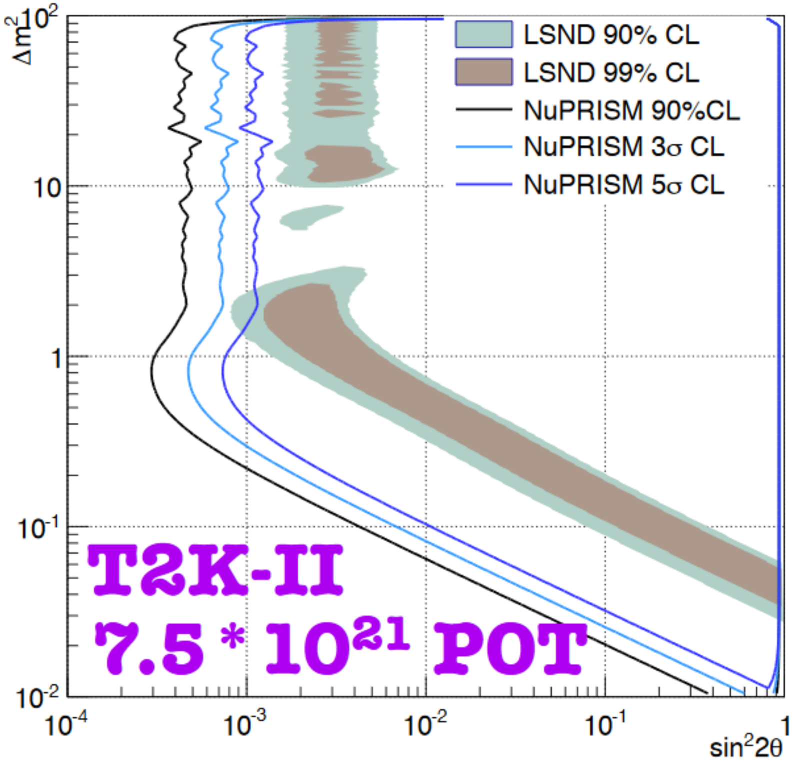
$\sin^2\theta_{23} = 0.5$
$\Delta m^2_{32} = 2.41\text{x}10^{-3}$



- Use data to directly predict oscillated spectrum (red)
- Backgrounds (green) can be measured in-situ
- Oscillation analysis minimally dependent on neutrino interaction model

PRISM benefits - 4





- Fit ND ν_e flux
  - Directly measure electron/muon cross-section ratio

- Sterile neutrino searches
  - >5σ exclusion of LSND
  - Oscillation vs off-axis angle